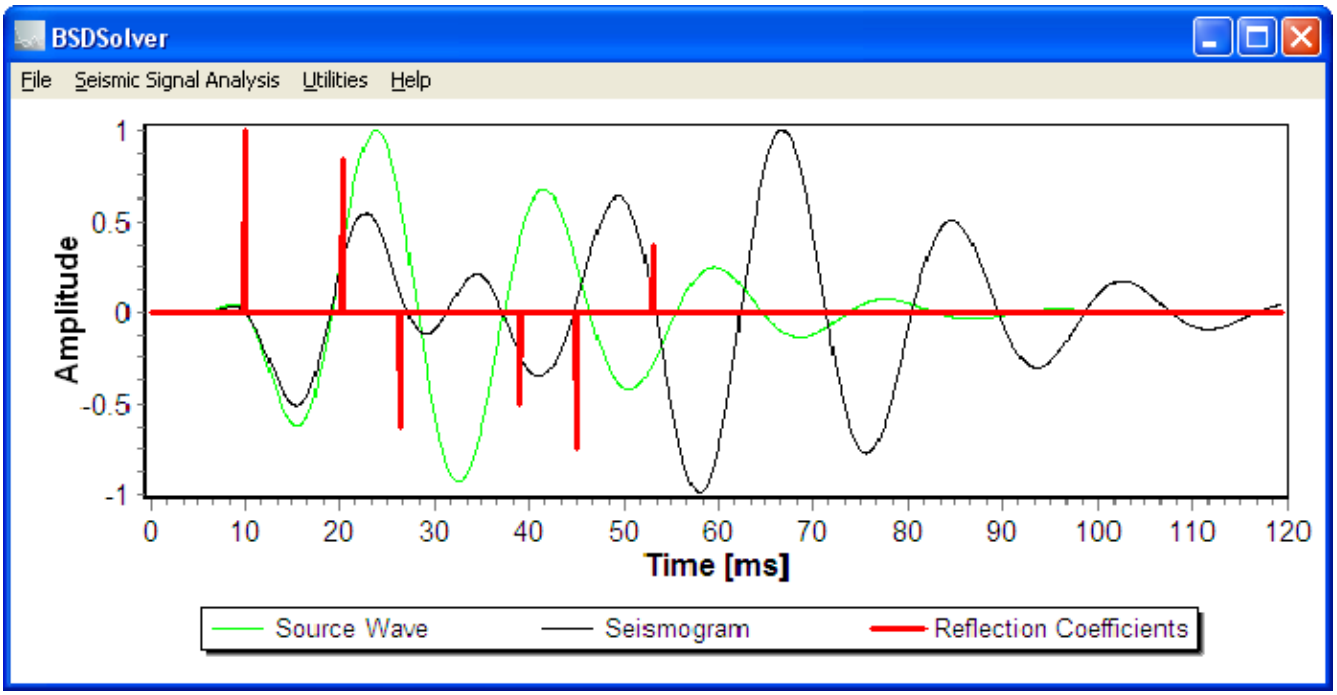
BSDSolver/2.0

User's Reference Manual



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1.0 Introduction

1.1 What is BSDSolver™?

BSDSolver™ is a program that facilitates the implementation of the Principle Phase Decomposition ***PPD***™ technique [1], [2] & [3]. It uses a seismic deconvolution algorithm, which allows for the estimation of the source wave and reflection series.

Seismic deconvolution is one of the most widely researched and implemented seismic signal processing tools. The primary goal of seismic deconvolution is to remove the characteristics of the source wave from the recorded seismic time series so that one is ideally left with only the reflection coefficients. These coefficients identify and quantify the impedance mismatches between different geological layers, which are of great interest to the geophysicist.

A very challenging and yet common seismic deconvolution problem is where the source wave is unknown and has the potential for time variation. This is referred to as blind seismic deconvolution (BSD): the situation where we have one known (measured seismogram with additive noise) and two unknowns (source wave and reflection coefficients). *PPD*™ is designed to solve blind seismic deconvolution problems.

BSDSolver™ includes the following features:

- Configurable for either geophones or accelerometers.
- Extensive frequency spectrum analysis.
- Bandpass, high pass, low pass, and notch frequency digital filters.
- Vertical seismic profile display with trend line estimation.
- Display of peak particle accelerations, velocities and displacements.
- Implementation of the PPD™ technique for source wave and reflection series estimation.
- Implementation of the water level technique for reflection series estimation based on an inputted PPD™ estimated source wave.
- Extensive chart editing, plotting, and exporting functions.

1.2 Organization of user's manual

The purpose of this manual is to instruct users of ***BSDSolver***™ in the use of the program by explaining the mathematical background and the program structure, taking the user step by step through the program menus, and specifying the use of interactive graphics and I/O routines.

2.0 PPD™ Mathematical Background

PPD™ is an analysis technique that facilitates blind seismic deconvolution allowing for the estimation of the source wave and reflection series. In seismology, the most important seismic model is, in general terms, written as [1]

$$z(t) = S(t) * \mu(t) + v(t) \tag{1}$$

where

- *z(t) :* the measured seismogram.
- *S(t)* : the seismic wave which is a superposition of earth and instrument responses.
- $\mu(t)$: the reflectivity of the earth which consists of all primary reflections as well as all surface and internal multiples.
- *v(t)*: the additive noise, generally taken to be white with a Gaussian pdf.
- $*$: denotes the convolution operation.

A fundamental task for the seismologist is to estimate the impedance as a function of the depth from the recorded seismogram. A commonly adopted simple model in applied seismology is that of a horizontally layered, one dimensional earth, referred to as the Goupillaud layered medium [1]. Here the impedance of the *k*th layer is defined as

$$\varepsilon_k = \rho_k V_k \tag{2}$$

where ρ_k and V_k are the density and velocity in the *k*th layer, respectively. The relationship between ε_k and μ_k, the reflection coefficient (assuming only primary reflection) of the *k*th layer, is

$$\mu_k = \frac{\varepsilon_{k+1} - \varepsilon_k}{\varepsilon_{k+1} + \varepsilon_k} \tag{3}$$

Rearranging (3) gives

$$\varepsilon_{k+1} = \varepsilon_k \left(\frac{1+\mu_k}{1-\mu_k} \right) = \varepsilon_1 \prod_{j=1}^{k} \left(\frac{1+\mu_j}{1-\mu_j} \right) \tag{4}$$

Therefore, it is required to estimate the reflection series, μ_k in order to determine ε_k. This means that in extracting the reflection series the source wave must first be estimated and then deconvolved from the recorded seismogram.

An alternative mathematical representation of the recorded time series, *z(t)*, defined in (1) is given as

$$z(t) = \int_o^t \mu(\tau) S(t-\tau) d\tau + v(t) \tag{5}$$

The discrete representation of (5) is given as

$$z(k) = \sum_{i=1}^{k} \mu(i) S(k-(i-1)) + v(k), \quad k = 1, 2 \cdots N \tag{6}$$

where N is the length of the time series.

The primary goal of seismic deconvolution is to remove the characteristics of the source wave from the recorded seismic time series, so that one is ideally left with only the reflection coefficients. These coefficients identify and quantify the impedance mismatches between different geological layers that are of great interest to the geophysicist. A very challenging and yet common seismic deconvolution problem is where the source wave is unknown. This is referred to as blind seismic deconvolution (BSD): the situation where we have one known (measured seismogram with additive noise) and two unknowns (source wave and reflection coefficients).

In the PPD™ algorithm an innovative model of the source wave is utilized. This source wave model is referred to as the amplitude modulated sinusoid (AMS) [1],[2] and [3]. The AMS is demonstrated to be a highly robust and accurate approximation for many analytical representations of seismic source waves, such as the exponentially decaying cyclic waveform, the mixed-phase Berlage wave, the zero-phase Ricker wave, and the zero-phase Klauder wave. In addition, the AMS wave has proven to be very accurate in modeling seismic data acquired during passive seismic monitoring and vertical seismic profiling.

The mathematical representation of the AMS source wave is given as

$$x_1(t) = x_2(t)\sin[\omega t + \varphi] \tag{7}$$

where $x_1(t)$ is an approximation to the seismic source wave, $x_2(t)$ is the seismic wave's amplitude modulating term (AMT), ω is the dominant frequency of the wave, and φ is the corresponding phase.

Amini and Howie [4] and [5] utilized a finite difference program (FLAC) to model downhole seismic source waves. Figure 1 illustrates the simulated source wave generated by Amini and Howie obtained by personal communication. This source wave was generated by assuming a uniform halfspace with an in-situ shear wave velocity of 180 m/s and a sampling interval of 0.02 ms. Superimposed upon this finite difference source wave is a scaled 140 Hz sinusoid with zero crossing at 10.3 ms as well as an exponential decay peaking at 15 ms and decaying at an exponential rate of 0.8/ms.

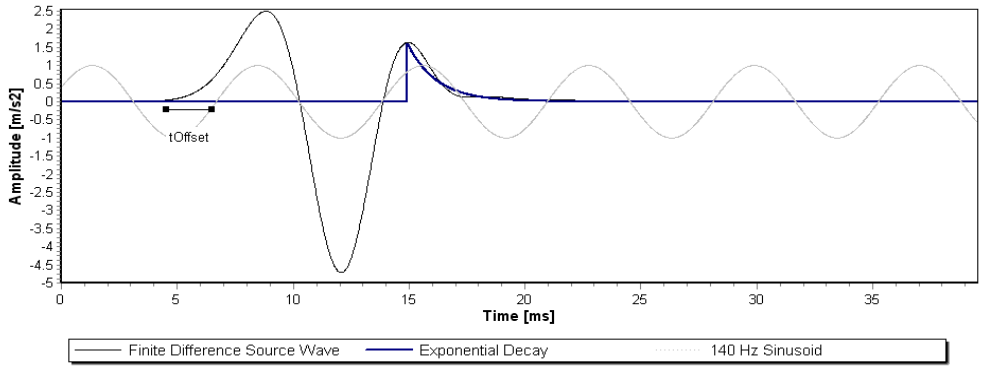

Figure 1: Finite difference source wave with superimposed 140 Hz sinusoid and exponential decay with rate 0.8/ms.

The three parameters that define the AMS source wave can then be described as follows:

- ω: the source wave's dominant frequency
- t_{Offset}: the offset time from the arrival time of the source wave (t_0) to the start of the sinusoidal component. This parameter is inherently related to the phase φ due to the fact that the arrival time of the source wave (t_0) is readily obtained from the seismogram.
- h: the exponential decay rate of the source wave.

Before implementation of the PPD™ algorithm there are three main parameters that must be specified:

1) The maximum possible length of the source wave (T_{max}).
2) The maximum number of possible overlapping source waves (N_{max}).
3) The minimum time separation between the reflection coefficients (RT_{min}).

Parameter T_{max} defines the maximum possible length of the source wave from the initial start until 95 % of the signal has decayed. This parameter is unlikely to exceed *2.5T* where *T* is the corresponding period of the dominant frequency of the source wave (i.e., $T = 1/f$ where $f = \omega/2\pi$). For example, the finite difference source wave of Amini and Howie outlined in Figure 1 has an approximate source wave time length of *1.5T*.

Parameter N_{max} defines the maximum number of reflection coefficients within the source wave time span. N_{max} does not reflect the total number of reflection coefficients within the seismogram, but the maximum number of reflection coefficients which can reside within the time duration of the source wave. This concept is illustrated in Figure 2 where a source wave is superimposed upon a series of reflection coefficients. As is illustrated in Figure 2, there are a total of 15 reflection coefficients within the seismogram that covers a 110 ms time span. The source wave shown in Figure 2 has a time duration of approximately 32 ms (from 10 to 42 ms) and only 5 reflection coefficients reside within that time span. Since it is very unlikely that there are more reflection coefficients in a source wave, the default value of N_{max} is set at 5.

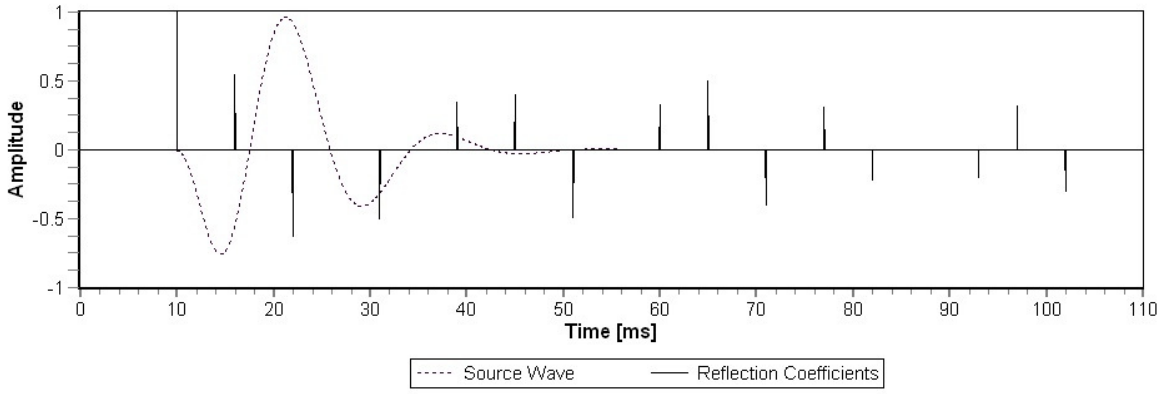

Figure 2: Illustrating the concept behind parameters T_{max} and N_{max}.

Parameter RT_{min} allows for constraining of the PPD™ algorithm solution space. For example, the reflection coefficients R_0, R_1, R_2, R_3,.. R_N must arrive subsequently later within the time series (i.e., $t_1<t_2<t_3..,t_N$) based upon the physics of reflection seismology. Parameter RT_{min} allows the investigator to set the minimum allowable time separation between the reflection coefficients. The maximum resolution (i.e., minimum RT_{min} specification) capability of the PPD™ algorithm is dependent upon the input parameter values such as the user specified dominant frequency analysis window and the properties of the additive measurement noise. The RT_{min} parameter defaults to 3ms due to the fact that it is unlikely that the reflection coefficients would be time separated less than 3ms [1] and to reduce computational requirements for smaller spaced reflection coefficients[1]. As expected, with smaller values of parameters T_{max} and N_{max} and a larger value of RT_{min} it will take less time for the program to process the seismic data.

The PPD™ program is designed to process two closely spaced seismograms simultaneously utilizing multi-threading and making use of standard dual-core processor technology. This is done so that the solution space for estimating the source wave is reduced. For example, in a typical downhole seismic investigation, the receivers are offset by 1 m. This 1 m offset is equivalent to a 10 ms source time offset for a medium velocity of 100 m/s. It is therefore very likely that two source waves offset by 10 ms are identical. By processing two seismic traces simultaneously, the PPD™ algorithm determines the top source wave estimates where the weighted RMS difference between the estimated seismograms and the true seismograms over time window t_0 (source wave arrival time) to $t_0 + T_{max}$ are minimized. The weight of the cost function is then defined as the absolute sum difference between the source wave parameters (i.e., ω, t_{Offset}, h, and the time location T' of the maximum peak of the source wave):

$$weight = abs(f_1 - f_2) + abs(T_1^{/} - T_2^{/}) + abs(h_1 - h_2) + abs(t_{offset1} - t_{offset2}) \tag{8}$$

The minimum and maximum source wave attenuation values are automatically estimated within the PPD™ algorithm based on the user specified minimum (f_{min}) and maximum (f_{max}) dominant frequency window of the source.

Minimum attenuation value:

The exponential decay is defined as $X = X_0 e^{-h\Delta t}$. If the amplitude of the AMT has decayed to 0.05 (5%) of the maximum value AMT_{MAX}, then $0.05 = e^{-h\Delta t}$ or $h\Delta t = 3$. Since it can be assumed that the maximum source length is $2.5T$ and that it will take at least 0.25T to reach AMT_{MAX} from t_0 (as is the case with every sine wave), the time for the source wave to decay to 5% of AMT_{MAX} is therefore at most $2.25T$. This means that

$$h_{\min} = 3/2.25T_{\max} = 1.333 f_{\min}$$

if $f_{min} = 50\ Hz$ then $h_{min} = 66.665/sec$ or $0.066665/ms$.

[1] Although a default value for RT_{min} of 3ms values have been specified, it is the intention of BCE ltd. to explore and quantified this issue further.

Maximum attenuation value:

Based on analytical source wave representations and numerous real data examples it can be assumed that the time for the source wave to decay to 5% of AMT_{MAX} is at least *0.5T*. This means that

$$h_{\max} = 3/0.5T_{\min} = 6f_{\max}$$

if f_{max} = *60 Hz* then h_{max} = *360/sec* or *0.36/ms*.

3.0 Main Menu

The main menu of ***BSDSolver***™, as illustrated in Figure 3, has four options:

- *File*
- *Seismic Signal Analysis*
- *Utilities*
- *Help*

The desired submenu is chosen either by moving the mouse over the desired option and pressing the left hand mouse button, by pressing function <F10> on the keyboard and selecting the desired highlighted option, or by pressing the corresponding menu item letter on the keyboard.

The seismograms processed by the *PPD*™ program are required to be in ASCII format with the sample rate (in ms) and depth at which the trace was acquired (in m) in the header, followed by the time series data. For example, the following excerpt from a standard *BSDSolver*™ file has the sampling rate specified as 0.05 ms, followed by the depth of 5 m which is subsequently followed by the time series data:

0.05
5
-6.34584242695294E-0003
-9.79220908943435E-0003
-1.32385757519157E-0002
-1.71980495395148E-0002

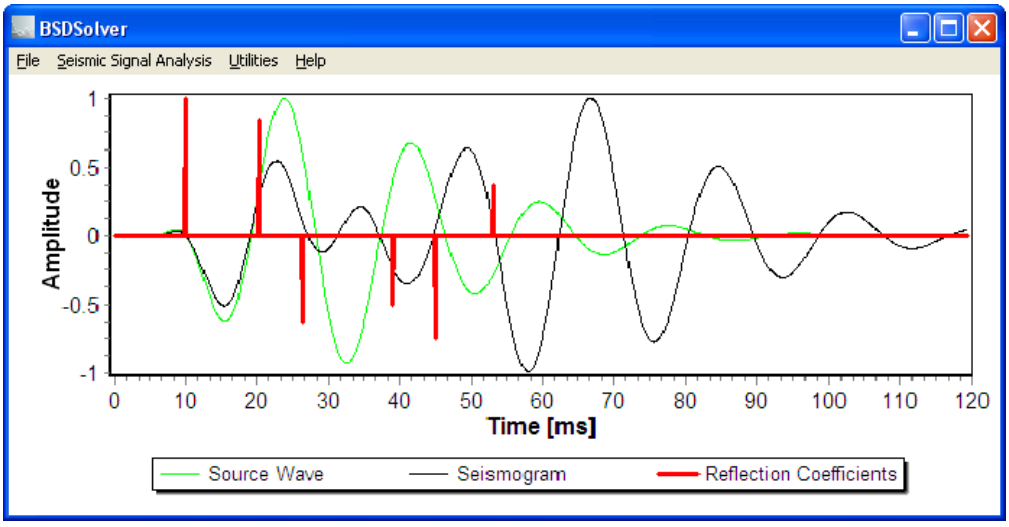

Figure 3:Main Menu in BSDSolver™

4.0 Seismic Signal Analysis

As is illustrated in Figure 4 the *Seismic Menu Analysis* menu option allows the user to carry out either a Blind Seismic Deconvolution (BSD) for source wave and reflection series estimation or implement the water level technique (WLT) for reflection series estimation based upon an inputted *PPD*™ estimated source wave. Selection of Main Menu option File->Open will also result in the initiation of a BSD analysis.

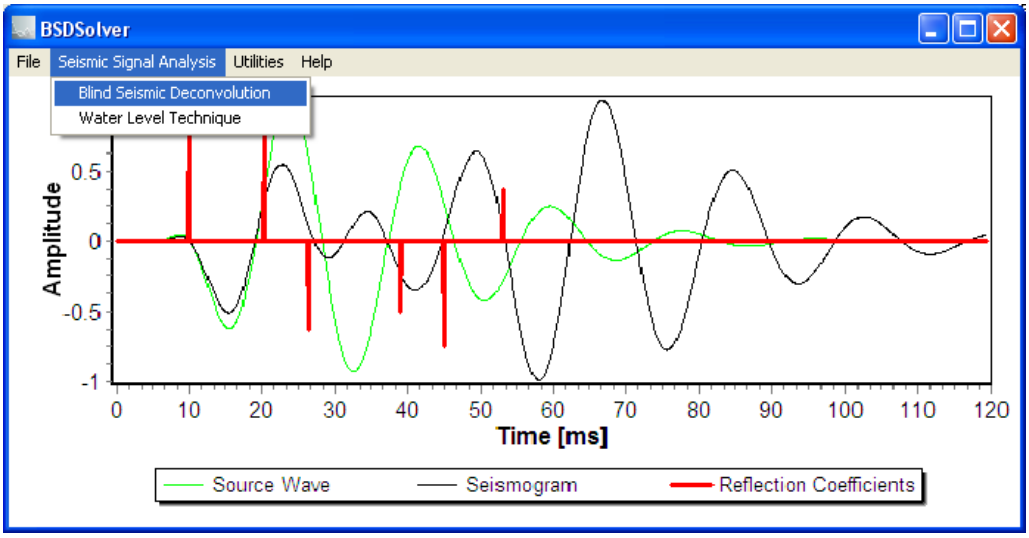

Figure 4: Seismic Signal Analysis software options

4.1 Blind Seismic Deconvolution

Selecting software option *Blind Seismic Deconvolution* opens the user interface as shown in Figure 5. As previously outlined in Section 2.1, the *PPD*™ algorithm is designed to process two closely spaced seismograms simultaneously utilizing multi-threading and making use of standard dual-core processor technology. This is done to reduce the solution space for estimating the source wave.

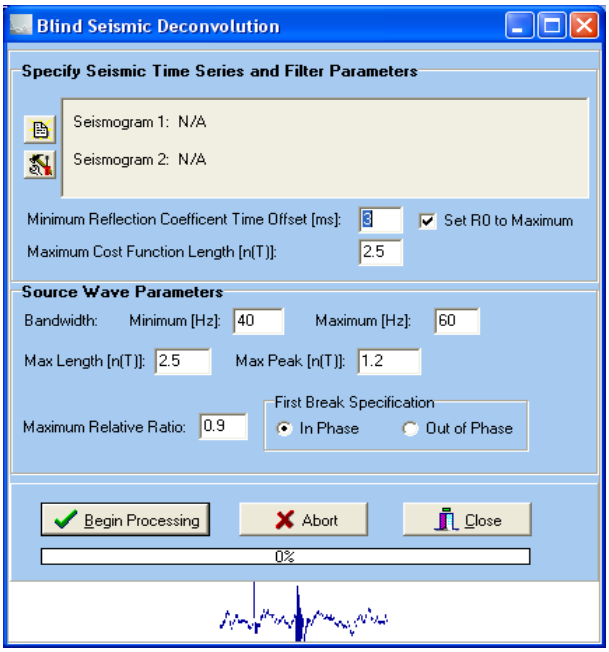

Figure 5: Blind Seismic Deconvolution user interface

4.1.1 Specifying Seismic Time Series and Filter Parameters

The seismogram files are inputted by selecting button , which opens the file input dialog window shown in Figure 6. In this window the user is instructed to input the two seismograms to be processed. If the user desires to process only one seismogram, then the same file should be selected twice.

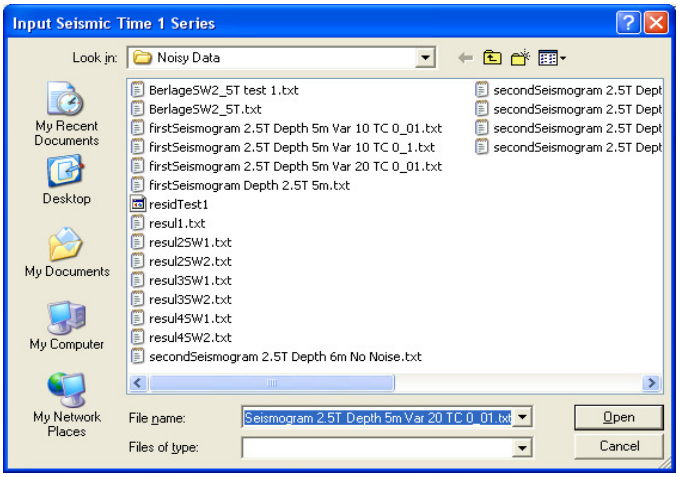

Figure 6: File input dialog box

The *PPD*™ algorithm requires that the seismograms are preprocessed so that the signal-to-noise ratio of the user specified seismograms is increased and ideally that the measurement noise is removed without distorting the seismogram containing only overlapping source waves.

User interface button allows the user to select a range of digital frequency filters (bandpass, notch, low pass, and high pass). Figure 7 illustrates the user interface which appears when button is selected.

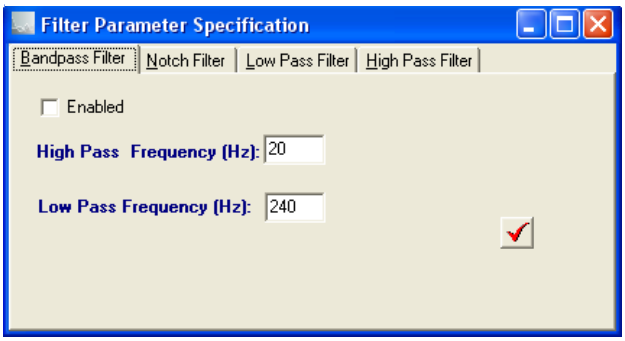

Figure 7: Filter Parameter Specification user interface

The appropriate filter is selected by opening the tab for that particular filter, checking the *Enabled* check box and entering the following data:

- for the *Bandpass Filter* the *High Pass Frequency* and *Low Pass Frequency*
- for the *Notch Filter* the *Notch Frequency*
- for the *Low Pass Filter* the *Low Pass Frequency*
- for the *High Pass Filter* the *High Pass Frequency*.

Once the desired digital frequency filters have been enabled and corresponding parameters specified the user selects button to save the entered data.

In addition the following must be done:

- *Enter the Minimum Reflection Coefficient Time Offset*
- *Enter the Maximum Cost Function Length (MCLF)*
- *Set R0 to Maximum*

The *Minimum Reflection Coefficient Time Offset* represents the RT_{min} parameter previously described in Section 2.0 and, as mentioned before, its default value is 3ms

The *MCFL* denotes the length of the time window length for which the error residual cost function (i.e. the RMS difference between the estimated seismogram and the true seismogram over time window t_0 (source wave arrival time) to t_0+*MCFL* (as shown in Figure 8) is calculated. It is specified as a multiple of *T* where *T* is the corresponding period of the dominant frequency of the source wave (i.e., $T = 1/f$ where $f = \omega/2\pi$) and its default value is *2.5T*. The *MCFL* should never be smaller than T_{max} due to the fact that we are estimating the complete source wave which has a maximum possible time length of T_{max}. However, the *MCFL* can exceed T_{max} if the number of reflection coefficients within the seismogram is less than or equal to N_{max}, i.e. in case of a so-called sparse reflection series. Such a sparse reflection series would be encountered for example when carrying out a vertical seismic profile within a remediation site containing stone columns. A larger value of the *MCFL* also allow for more time series information to be taken into account when minimizing the cost function within the *PPD*™ algorithm and thus provided greater accuracy and uniqueness in the source wave and reflection series estimation.

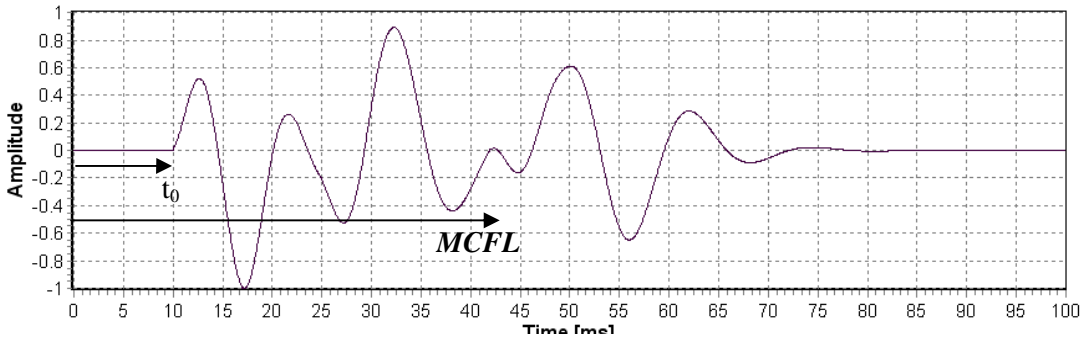

Figure 8: PPD™ cost function time window

Unless a residual wave is analyzed, the first arriving source wave has typically the largest amplitude. The user can specify this *a priori* within the *PPD*™ algorithm by setting R0 (reflection coefficient of first arriving source wave) to the maximum value in the reflection series within time length t_0 (source wave arrival time) to t_0+*MCFL*. This is implemented by enabling check box *Set R0 to Maximum* (default setting).

4.1.2 Specifying Source Wave Parameters

As outlined in Figure 5, the Source Wave Parameters required for user input are

- *Bandwidth*
- *Maximum possible length of the source wave (T_{max})*
- *Maximum possible time location of the maximum peak of the source wave (T'_{max})*
- *Maximum Relative Ratio (MRR)*
- *First Break Specification (FBS)*

These input parameters allow the user to provide *a priori* information of the source wave to be estimated. Input *Bandwidth* represents the source wave dominant frequency window. The user is required to specify the *Minimum* (f_{min}) and *Maximum* (f_{max}) dominant frequencies of the frequency window. It should be noted that the larger the source wave bandwidth the greater time is required to process the seismograms. Source wave input parameters of *Max Length*, *Max Peak*, *Maximum Relative Ratio* and *First Break Specification* are illustrated in Figure 9.

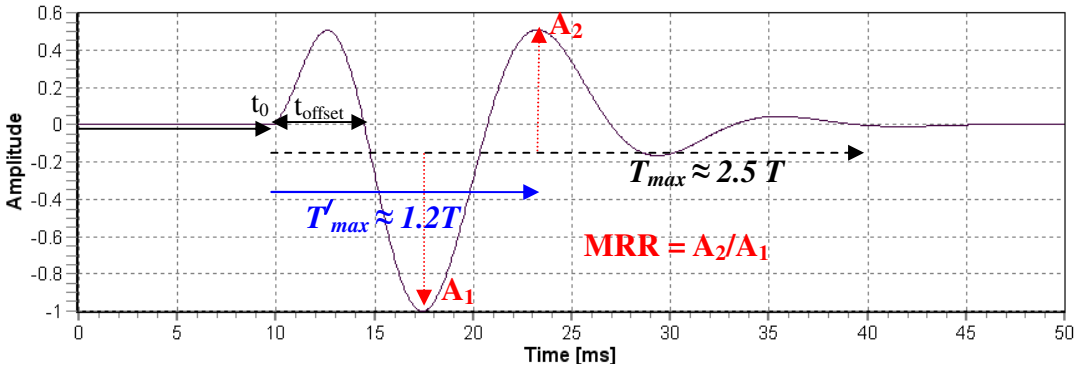

Figure 9: Source wave input parameters

The *Maximum Possible Length* (T_{max}) is specified as a multiple of T and the default setting is *2.5T*.

Parameter T'_{max} denotes the maximum possible time location of the maximum peak of the source wave from t_0 as is shown in Figure 9. It is specified as a multiple of T and the default setting is *1.2T*. It should be noted that seismic source waves are not maximum phase (i.e. energy concentrated at end of source wave); therefore, it would not be expected that the source wave would peak near the end of its time window.

The parameter *Maximum Relative Ratio* (*MRR*) is illustrated in Figure 8. The *MRR* parameter allows the user to specify a minimal decay of the source wave when moving from the maximum peak (A_1 in Figure 9) to the next peak (A_2 in Figure 9) at a *0.5T* time offset. It is expected that the source wave decays from the maximum peak and parameter *MRR* allows the investigator to specify a minimum decay ratio *a priori*. The *MRR* parameter default value is set to 0.9.

The *First Break Specification* (*FBS*) has two possible settings:

- *In Phase*
- *Out of Phase*

As previously illustrated in Figure 1, t_{Offset} is the offset time from the arrival time of the source wave (t_0) when the sinusoidal component commences. The source wave at time t_0 and $t_0 + t_{Offset}$ is *In Phase* if the amplitude values at times t_0 and $t_0 + t_{Offset}$ have the same sign (i.e., + or -) as shown in Figure 1. The source wave at time t_0 and $t_0 + t_{Offset}$ is *Out of Phase* if the amplitude values at times t_0 and $t_0 + t_{Offset}$ have different signs.

The standard procedure in selecting the FBS option is to first select two closely spaced seismograms or even the same seismogram twice, to process them and to determine the output RMS error residual after processing the data file with the *In Phase* option set. Next process the same data files utilizing option *Out of Phase* and determine once again the RMS error output. The *FBS* result which gives the lowest RMS error residual is then selected when processing the remaining seismic data generated from the same source mechanism and captured at that site.

When implementing the *PPD*™ algorithm it is important that the seismogram has an unambiguous first break or source wave arrival time (t_0) as illustrated in Figure 9. The source wave arrival time is determined automatically by initially normalizing the portion of the seismogram to be processed as shown in Figure 9 and then identifying the reference time ($t_{0.1}$) when the source wave exceeds amplitude 0.1. The first break or source wave arrival time (t_0) is then obtained by moving back in time from $t_{0.1}$ until the first zero crossing is reached.

Once the *Seismic Time and Filter Parameters* and the *Source Wave Parameters* have been specified the user selects push button *Begin Processing*.

4.1.3 Blind Seismic Deconvolution Implementation

The implementation of the *PPD*™ algorithm is demonstrated by considering the analysis of two challenging synthetic seismograms. The seismograms are challenging due to the fact that there are five closely spaced reflection coefficients with dipoles in a high measurement noise environment. The first seismogram was generated by convolving the Berlage wave illustrated in Figure 10 with the reflection coefficients outlined in Figure 11 to give the output illustrated in Figure 12. The second seismogram is generated by convolving the Berlage wave of Figure 10 with the reflection series illustrated in Figure 13. The resulting seismogram is shown in Figure 14. Table I outlines the reflection series parameters of arrival time and amplitude for seismograms 1 and 2.

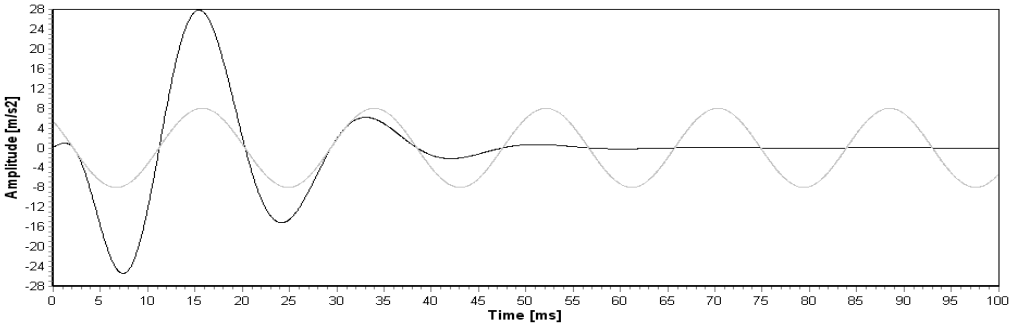

Figure 10: Berlage wave with superimposed 55 Hz sinusoid

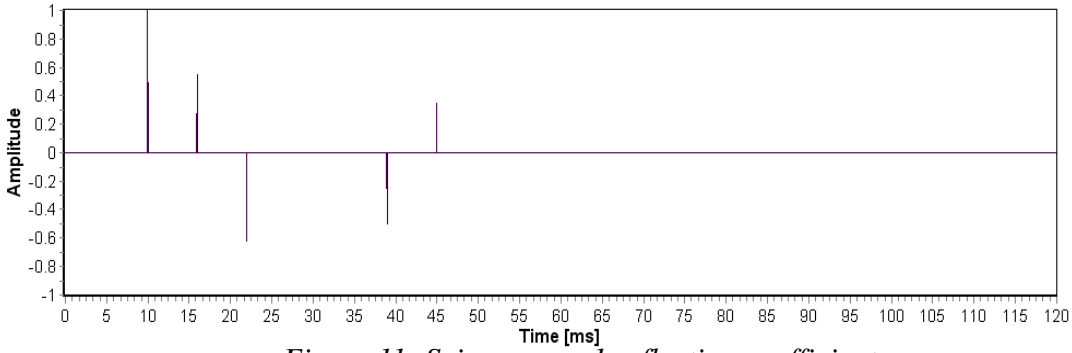

Figure 11: Seismogram 1 reflection coefficients

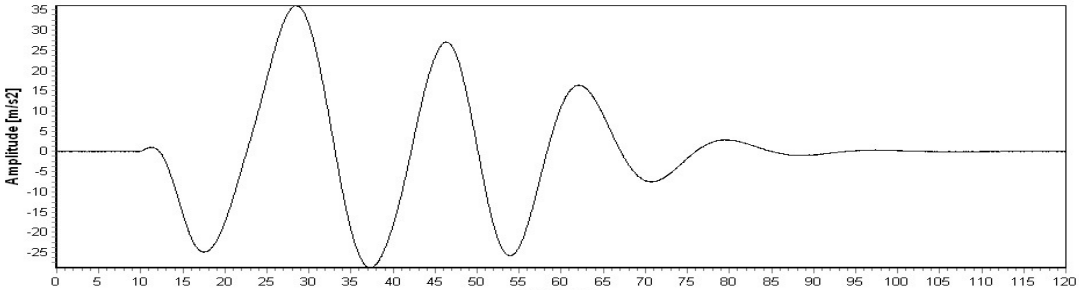

Figure 12: The output after convolving Berlage wave of Figure 10 with reflection coefficients illustrated in Figure 11.

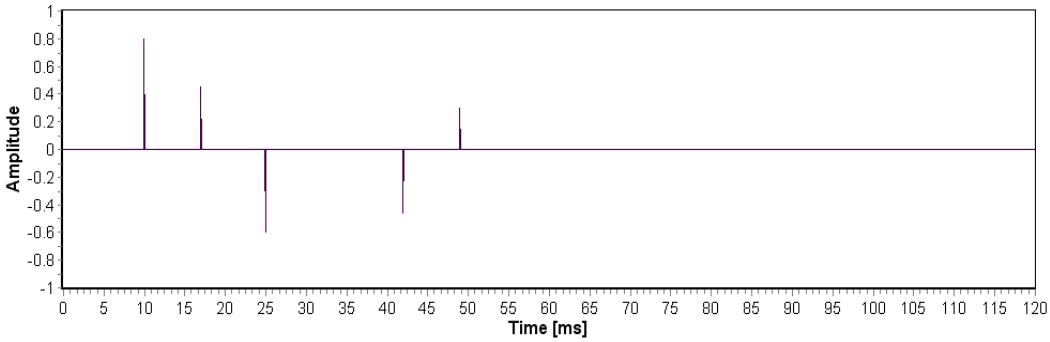

Figure 13: Seismogram 2 reflection coefficients.

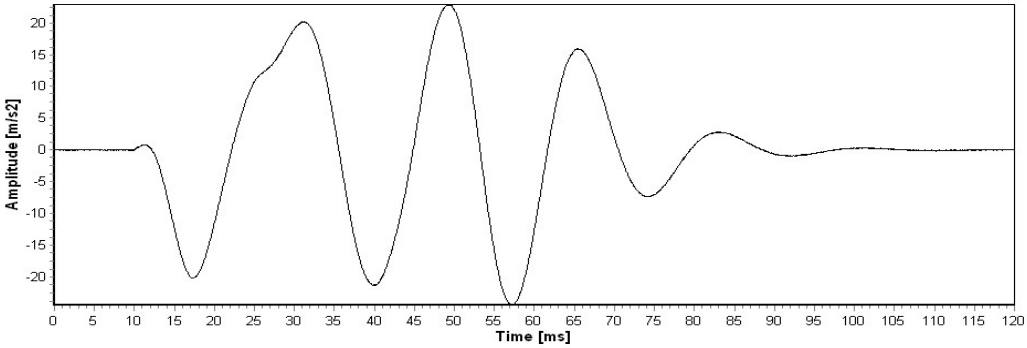

Figure 14: The output after convolving Berlage wave of Figure 10 with reflection coefficients illustrated in Figure 13

TABLE I
REFLECTION SERIES PARAMETERS

Seismogram 1		Seismogram 2	
Reflection Coefficients		Reflection Coefficients	
Time [ms]	Amplitude	Time [ms]	Amplitude
10	1.0	10	0.8
16	0.55	17	0.45
22	-0.625	25	-0.6
39	-0.5	42	-0.46
45	0.35	49	0.3

As is evident from Figures 11 and 13 and Table I, the reflection series for seismograms 1 and 2 are very similar, which would be the case where we have recorded seismic traces from two relatively closely spaced receivers. Although there are minor variations between the reflection series of seismograms 1 and 2, the resulting seismograms have significant differences as illustrated in Figures 12 and 14. To these synthetic seismograms a Gauss-Markov measurement noise was added with a variance and time constant set to 10 units^2/s^2 and 0.01 ms respectively, and the outcome is shown in Figures 15 and 16.

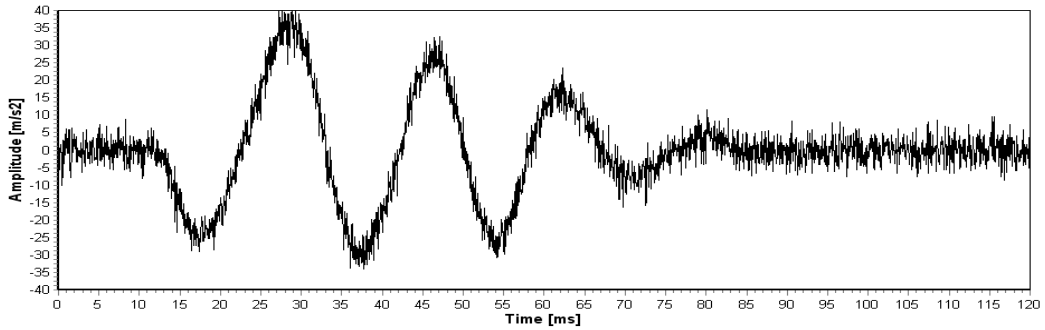

Figure 15: Seismogram of Figure 12 with additive Gauss-Markov measurement noise.

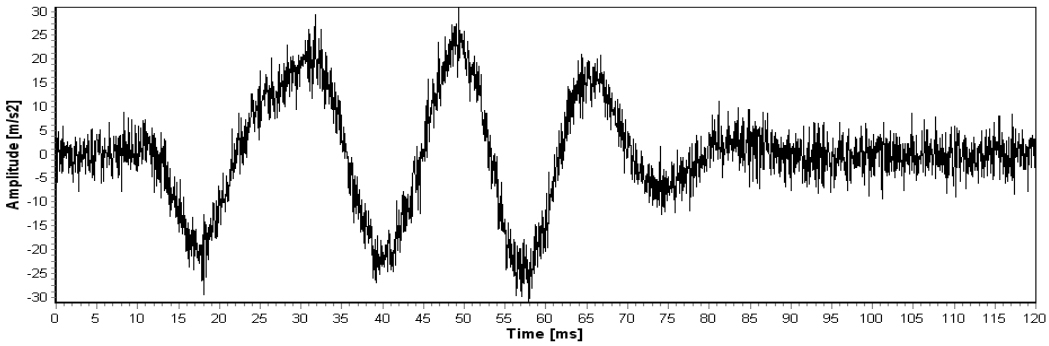

Figure 16: Seismogram of Figure14 with additive Gauss-Markov measurement noise.

These seismograms are stored in data files *firstSeismogram 2.5T Depth 5m Var 10 TC 0_01.txt* and *secondSeismogram 2.5T Depth 6m Var 10 TC 0_01.txt*, respectively, and pre-processed with a 200 Hz low-pass zero phase digital filter as illustrated in Figure 17.

The filtered seismograms are then fed into the *PPD*™ algorithm with parameters f_{min}, f_{max}, and RT_{min} set

to 45 Hz, 60Hz, and 3 ms, respectively. In addition, the parameters *MCFL*, T_{max}, T'_{max}, and *MRR* are set to 2.5, 2.5, 1.2 and 0.9, respectively. The FSB parameter is set to *In Phase* and *Set R0 to Maximum* is enabled. The parameter settings are illustrated in Figure 18.

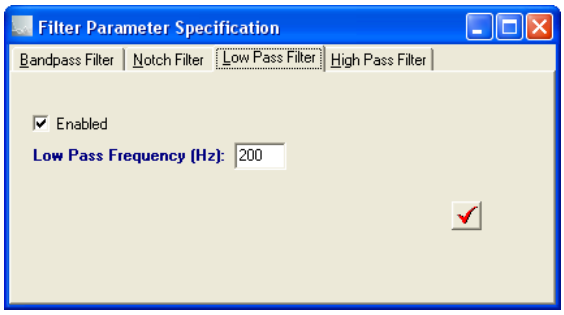

Figure 17: Specifying a 200 Low Pass Filter

These settings were selected for the following reasons:

- The source bandwidth specification of 45 Hz to 60 Hz was based upon experience and the frequency spectra of the seismogram utilizing *BSDSolver*™ option *Utilities->View Seismogram* as outlined in Section 5.2 and Figures 35 and 36. .
- T_{max} was set to the default value of 2.5T due to the fact that we have no *a priori* information on the time length of the source wave and source waves do not general exceed time lengths of 2.5T.
- *MCFL* was set to the default value of 2.5T due to the fact that there is no reason to assume that we are dealing with a sparse reflection series.
- T'_{max} was set to 1.2T based upon experience and the fact the source waves tend to be minimum and mixed phase.
- Parameter *MRR* is set to the default value of 0.9 due to the fact that we would expect some decay moving from the maximum peak to the next peak.

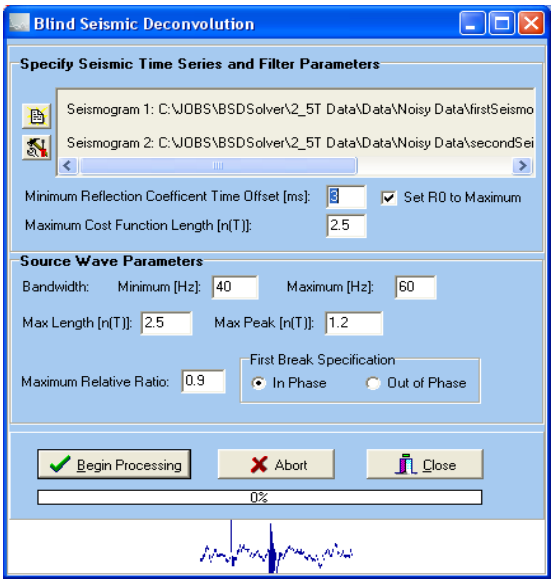

Figure 18: BSDSolver™ Parameter Settings

Once the input parameters have been specified the *Begin Processing* push button is selected.

The output from the *PPD*™ algorithm is shown in Figure 19. The top chart of Figure 19 shows the normalized estimated source wave, normalized estimated reflection series and normalized estimated seismogram (from time span t_0 to t_0+*MCFL*) for the low pass filtered data file shown in Figure 15. Also illustrated is the normalized true low pass filtered seismogram and the error residual between the estimated seismogram (calculated by convolving the estimated reflection series with the estimated source wave) and the true filtered and normalized seismogram between time span time span t_0 to t_0+*MCFL*. It should be noted that in the top chart display the first break value t_0 and subsequent first arriving reflection coefficient are set arbitrarily at a reference of time 10 ms. In the bottom chart of Figure 19 the estimated reflection series and seismogram have shifted to the true t_0 value.

Displayed in the top panel above the top chart in Figure 19 is the estimated source wave dominant frequency (*DF[Hz]: 56.1*), attenuation (*h[1/ms]: 0.1054*) and RMS error residual between the true seismogram and estimated seismogram (*RMS Error: 0.004335*). Selecting button within the top panel located above the top chart will result in the chart editing user interface illustrated in Figure 20.

Section 6.0 outlines the chart formatting, editing and printing capabilities of the *BSDSolver™* program. The user can enable and disable the display of a desired series by checking and un-checking the appropriate check box, respectively. For example, Figure 21 illustrates only the seismogram error residual time series within the top chart. User interface buttons and allow for the removal and display of all the time series, respectively.

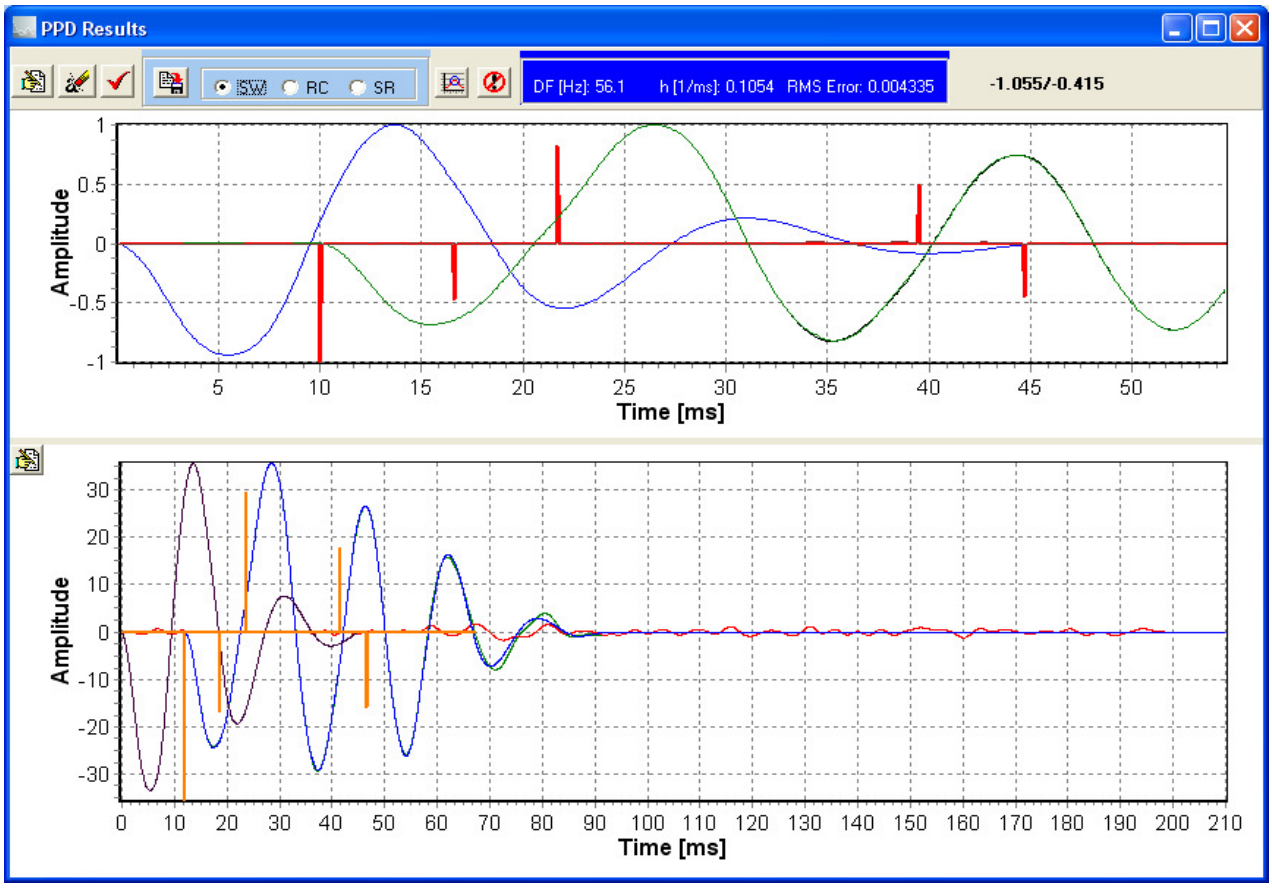

Figure 19: BSDSolver™ algorithm output after processing the noisy seismograms illustrated in Figures 15 and 16 with a 200 Hz low pass filter applied

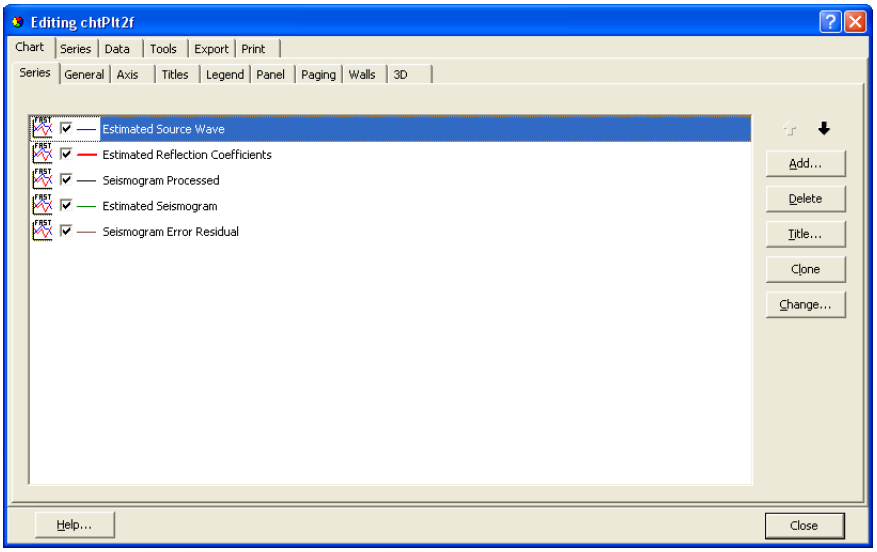

Figure 20: BSDSolver™ program chart editing, formatting and printing user interface

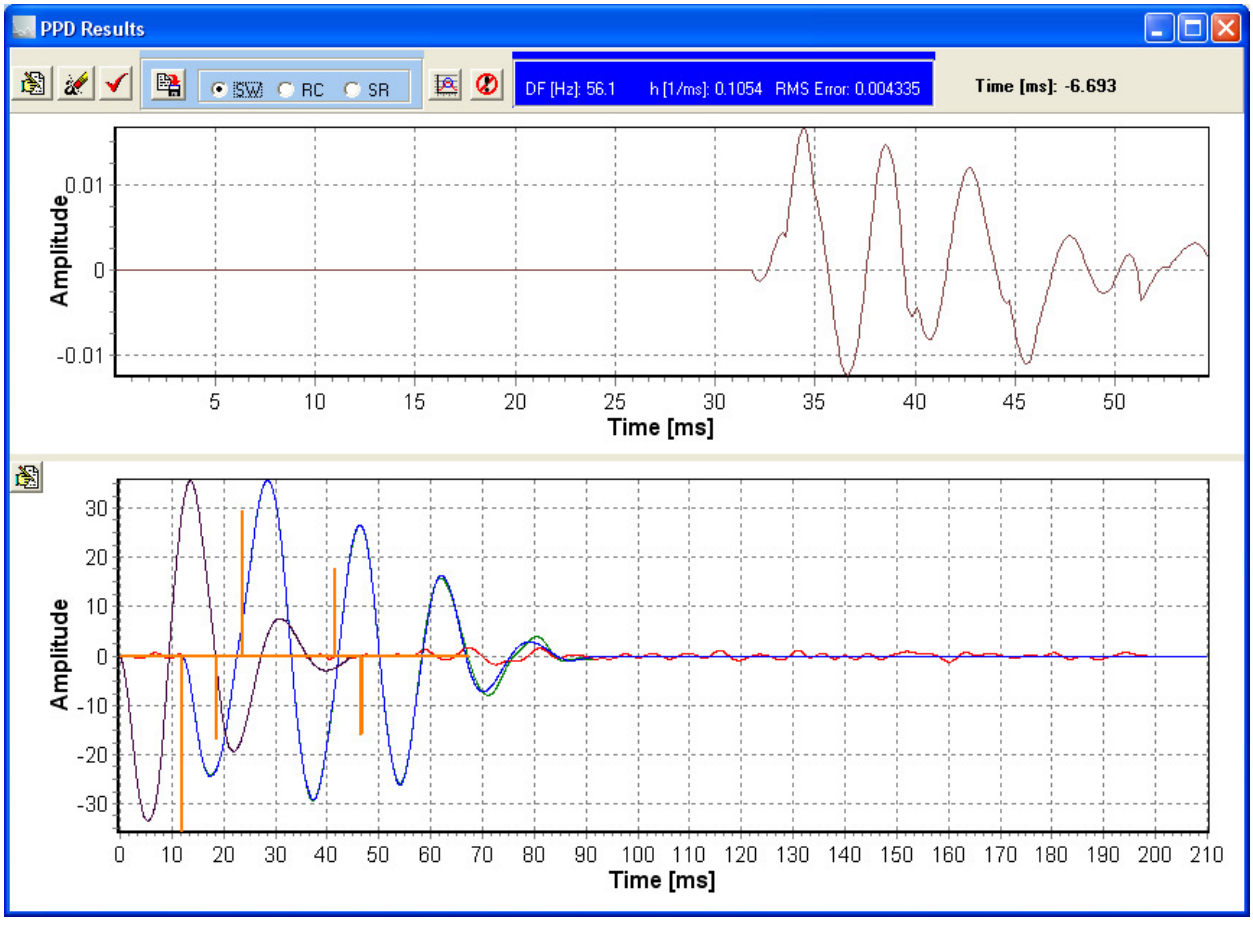

Figure 21: Display of seismogram error residual time series

The bottom chart illustrated in Figures 19 and 21 is similar to that of the top chart, but in this case the complete seismogram is displayed unnormalized and the estimated seismogram (calculated by convolving the estimated reflection series with the estimated source wave) is derived over the complete length of the recorded seismogram. The estimated source wave and reflection series have been scaled by the windowed seismogram normalization factor by selecting button . The scaling of the estimated source wave and reflection series can be undone by selecting button as is shown in Figure 22. The user should note that the signs (+/-) of the reflection coefficients are assigned based upon the estimated first break sign of the estimated source wave. For example, the estimated source wave of Figure 19 has a negative first break resulting in a negative sign for the first reflection coefficient.

The estimated source wave, estimated reflection series and residual seismogram can be saved by selecting the appropriate radio button (*SW*, *RC* and *SR*, respectively) and pressing button . The user is then instructed to specify the file name and directory as is illustrated in Figure 23.

The source wave estimate illustrated in Figures 19 and 21 is then utilized to deconvolve the source wave from the seismogram by implementing the water level technique (WLT) so that the complete reflection series is obtained. The implementation of the WLT is a fast and simple approach if there is minimal source wave variation within the seismogram. If, however, significant source wave variation did occur within the seismogram then a recursive *PPD*™ approach could be utilized. In that case the *PPD*™ algorithm is applied recursively to the residual seismogram until the total seismogram has been processed and the complete reflection series is estimated.

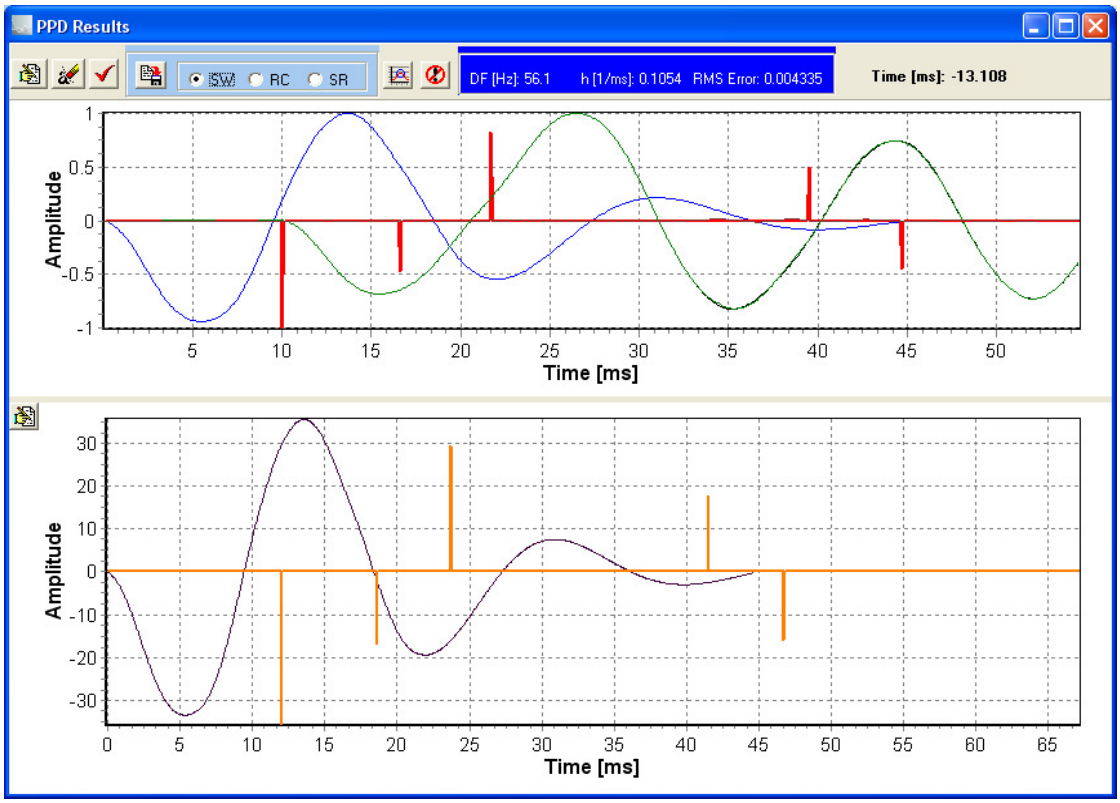

Figure 22: Normalized estimated source wave and reflection series

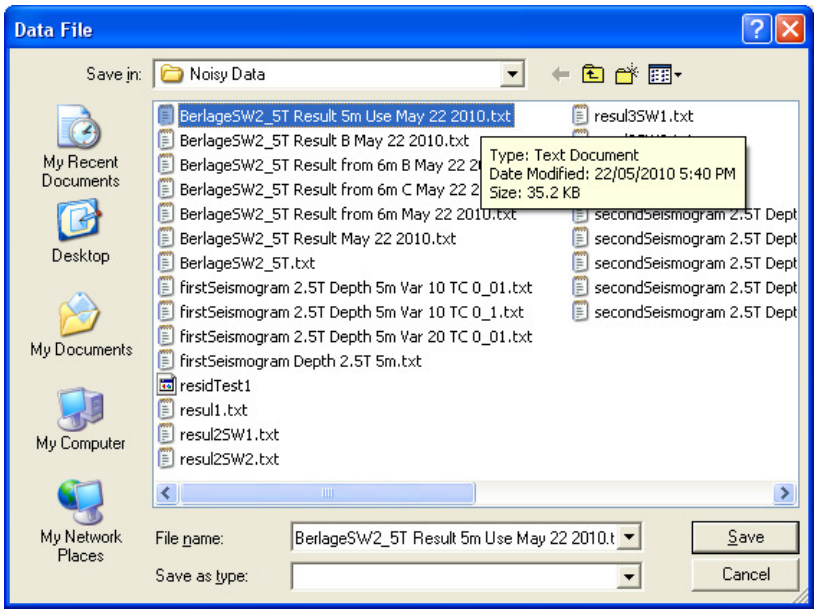

Figure 23: Saving the estimated source wave, reflection series, and residual seismogram

The user can reprocess the previously outlined data set with a larger *MCFL* value setting if they have some insight into the testing environment. For example, Figure 24 illustrates a downhole seismic testing (DST) investigation within a remediation site where there are stone columns present. In this situation it would not be expected that there would be more than 3 (direct wave and two reflections) to 4 overlapping source waves.

If the user does not have insight into the seismic testing environment a larger *MCFL* value setting can be specified if there is a short duration seismogram and based upon results like those outlined in Figures 19, 21 and 22. In these figures it is evident that the last reflection coefficient occurs at the end of the seismograms and we are processing relatively short duration seismogram; therefore, applying a larger *MCFL* value makes intuitive sense.

The major advantage of increasing the *MCFL* value is that more accurate results are obtained due to the fact that a greater portion of the seismogram is utilized when calculating the cost function. The disadvantage is that significantly greater processing time is required.

The previously estimated seismograms had a source length and *MCFL* specified as *2.5T* which equates to an approximate duration (for an estimated 56 Hz dominant frequency (i.e., $T=1/f \approx 18$ *ms*) of *45 ms*. If we increase the *MCFL* value to a slightly larger value of *2.7T*, the new cost function length is then approximately 49 *ms*. The seismograms shown in Figures 15 and 16 are reprocessed for this value and the results for test case outlined in Figure 15 are shown in Figure 25. As is shown in the top chart of Figure 25, a slightly greater portion of the seismogram (t_0 + 2.7T = 59 ms) was utilized when minimizing the cost function compared to the results illustrated in Figures 19 (t_0 + 2.5T = 55 ms). However, the estimated source wave and reflection series shown in Figure 25 are very similar to those given in Figures 19, indicating that this increase in *MCFL* had minimal impact on the analysis outcome.

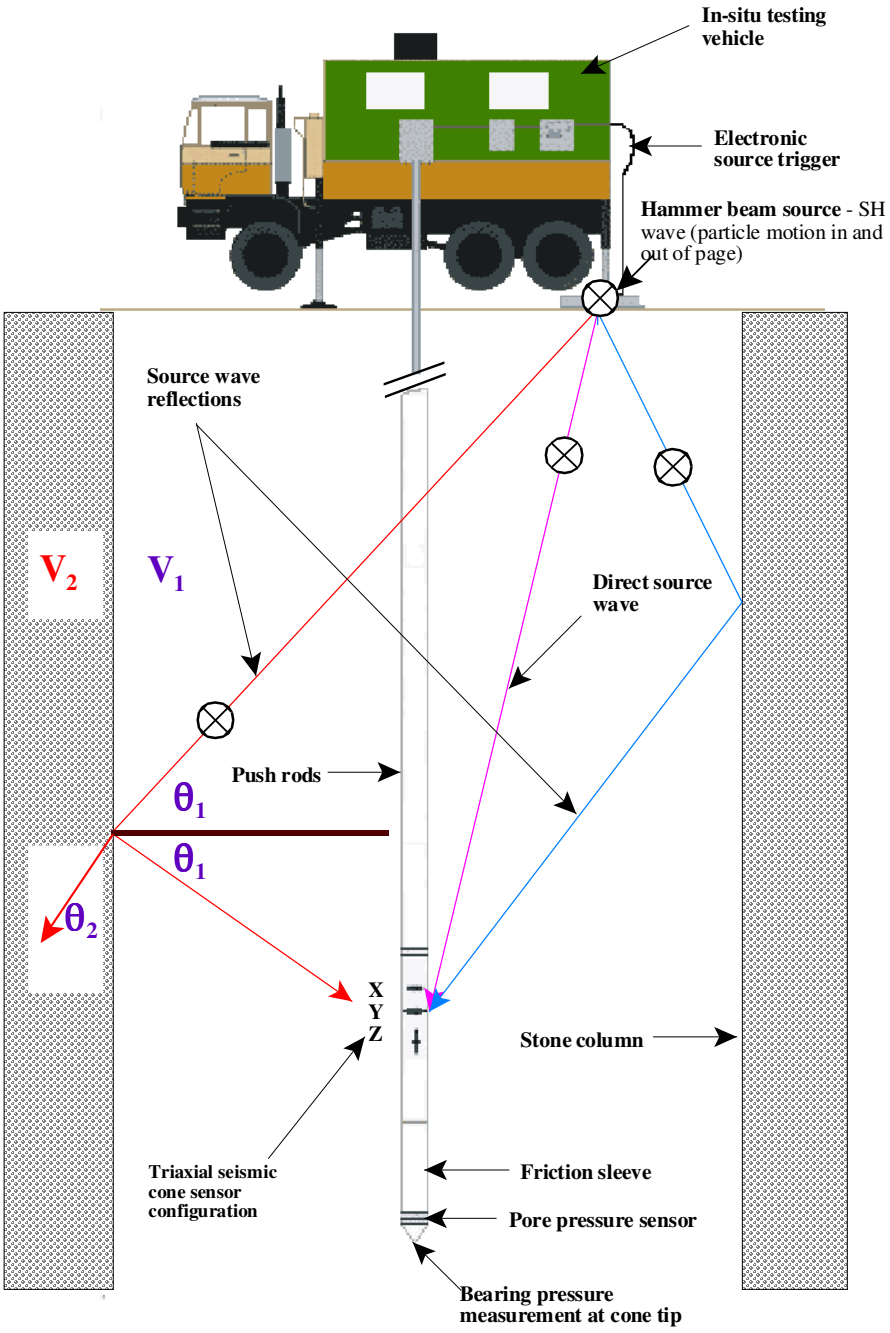

Figure 24. Illustration of overlapping source waves when conducting a SCPT investigation within a remediation site containing stone columns.

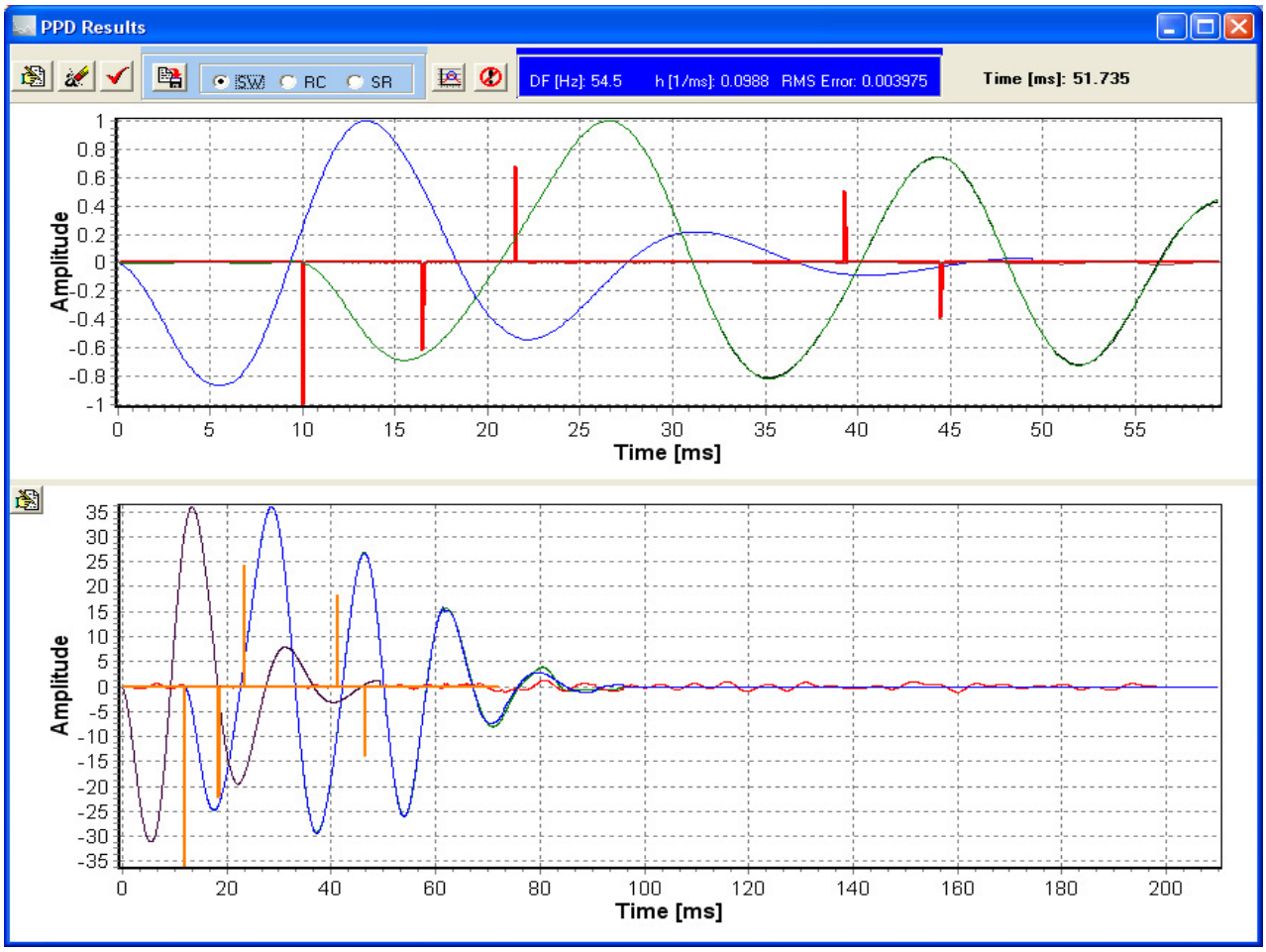

Figure 25. BSDSolver™ algorithm output after processing the noisy seismograms illustrated in Figures 15 and 16 with a 200 Hz low pass filter applied and a MCFL parameter setting of 2.7T.

4.2 Water Level Technique

As previously outlined, it is recommended that the user implement the WLT on the *PPD*™ source wave estimates. The implementation of the WLT is a fast and simple approach if there is minimal source wave variation within the seismogram.

4.2.1 WLT Theoretical Background

A standard frequency domain methodology in estimating the reflection series μ_k, is the water level technique (WLT) [2]. If the measurement noise term in (1) is ignored, then the Z transform of (1) is given as

$$z(t) = S(t) * \mu(t) \Leftrightarrow Z(z) = S(z)\Psi(z) \tag{9}$$

where $\Psi(z)$ denotes the Z transform of the reflection series

The WLT can be described by considering (9), representing the Z transform by the Fourier transform (i.e., $z = e^{i\omega t}$) and rearranging terms as follows:

$$\Psi(\omega) = \frac{Z(\omega)}{S(\omega)} \tag{10}$$

where $\Psi(\omega)$ denotes the Fourier transform of the reflection series $\mu(t)$. Theoretically, for a known source wave, one could simply implement (10) and calculate $\Psi(\omega)$. The reflection series, μ_k, is then estimated by taking the inverse Fourier transform of $\Psi(\omega)$. Unfortunately, due to inaccuracies in the specification of the source wave, the bandlimited nature of the source wave and additive measurement noise, the implementation of (10) is highly unstable and inaccurate.

To mitigate that, (10) is modified by multiplying the numerator and denominator by the complex conjugate of $S(\omega)$ (denoted as $S^*(\omega)$) and then by introducing an additive scalar value to the denominator which is referred to as the *water level* (Δ). Implementation of these two modifications to (10) gives

$$\Psi(\omega) = \frac{Z(\omega)S^*(\omega)}{S(\omega)S^*(\omega) + \Delta} = \frac{Z(\omega)S^*(\omega)}{P_S(\omega) + \Delta} \tag{11}$$

where $P_S(\omega)$ denotes the power spectrum of the source wave (i.e., the Fourier transform of the autocorrelation of $S(t)$). In general terms, the setting of the water level is a trial and error approach. As $\Delta \to 0$, the resulting estimated reflection coefficients approach Dirac delta functions. When $\Delta >> P(\omega)$ the resulting estimated reflection coefficients become significantly bandlimited and the result converges to the Fourier transform of the cross-correlation between the recorded seismogram and the source wave (i.e., $Z(\omega)S^*(\omega)$).

4.2.1 WLT Implementation

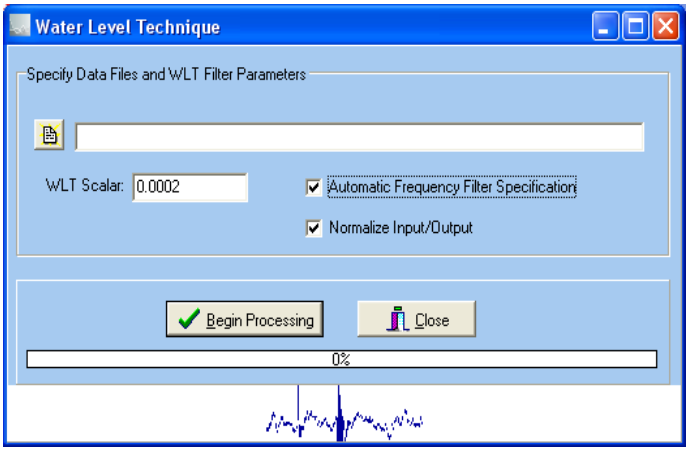

Figure 26: WLT main user interface

The main user interface for the WLT is shown in Figure 26. The first step in implementing the WLT is to specify the source wave and seismogram file by selecting . When button is selected the file input user interface is displayed (see Figure 6) where the user is requested to input the source wave file first and then the seismogram file. As outlined in Figure 24, the WLT parameters required for user input are

- *WLT Scalar*
- *Automatic Frequency Filter Specification*
- *Normalize Input/Output*

The *WLT Scalar* corresponds to the *water level* (*WL*) Δ in (11). In the *BSDSolver*™ program the user specified *WLT Scalar* value is scaled by the maximum power of the seismogram prior to inputting into (11). The default value of the WL is 0.0002. In general terms, the setting of the WL is a trial and error approach and depends upon the measurement noise level and the accuracy of the estimated source wave. A higher WL value is required if the seismogram to be processed has increasing measurement noise and decreasing source wave accuracy.

The estimated reflection coefficient amplitudes are highly affected by the value of the WL and whether a frequency filter had been applied to the seismogram prior to implementing the WLT. A higher WL value and application of a frequency filter (e.g., 200 Hz Low Pass) will result in a significant decrease in the resolution of the reflection series. This results in a more bell shaped reflection series (energy is spread out) whereby the peak values are reduced due to energy spreading. In other words, a high WL value has the same effect as a frequency filter (smoothing and spreading of energy of the reflection series).

As previously stated, as $\Delta \rightarrow 0$, the resulting estimated reflection coefficients approach Dirac delta functions and if measurement noise is present the reflection series become significantly indiscernible (e.g., white noise). When $\Delta >> P(\omega)$ the resulting estimated reflection coefficients become significantly bandlimited and the result converges to the Fourier transform of the cross-correlation between the recorded seismogram and the source wave (i.e., $Z(\omega)S^*(\omega)$).

If a check is placed within checkbox *Automatic Frequency Filter Specification* then the currently configured frequency filter(s) is/are applied automatically on the user specified seismogram prior to deconvolving the source wave. If the *Automatic Frequency Filter Specification* is disabled then the digital frequency filter user interface appears (see Section 4.1.1 and Figure 7) when the *Begin Processing* button is pressed.

Implementation (i.e., placing check in checkbox) of WLT option *Normalize Input/Output* will result in the source and seismogram in (11) being normalized prior to the implementation of (11). The estimated reflection series will also be normalized. This is the recommended configuration due to the fact that there can be significant energy leakage of the reflection series as previously described where the peak amplitudes of the estimated reflection coefficients are considerably reduced; therefore, it makes greater sense to normalized the reflection series.

Specifying the estimated source wave illustrated in Figures 19, 21 and 22 and seismogram shown in Figure 16 with a 200 Hz low pass filter results in the WLT output illustrated in Figure 27.

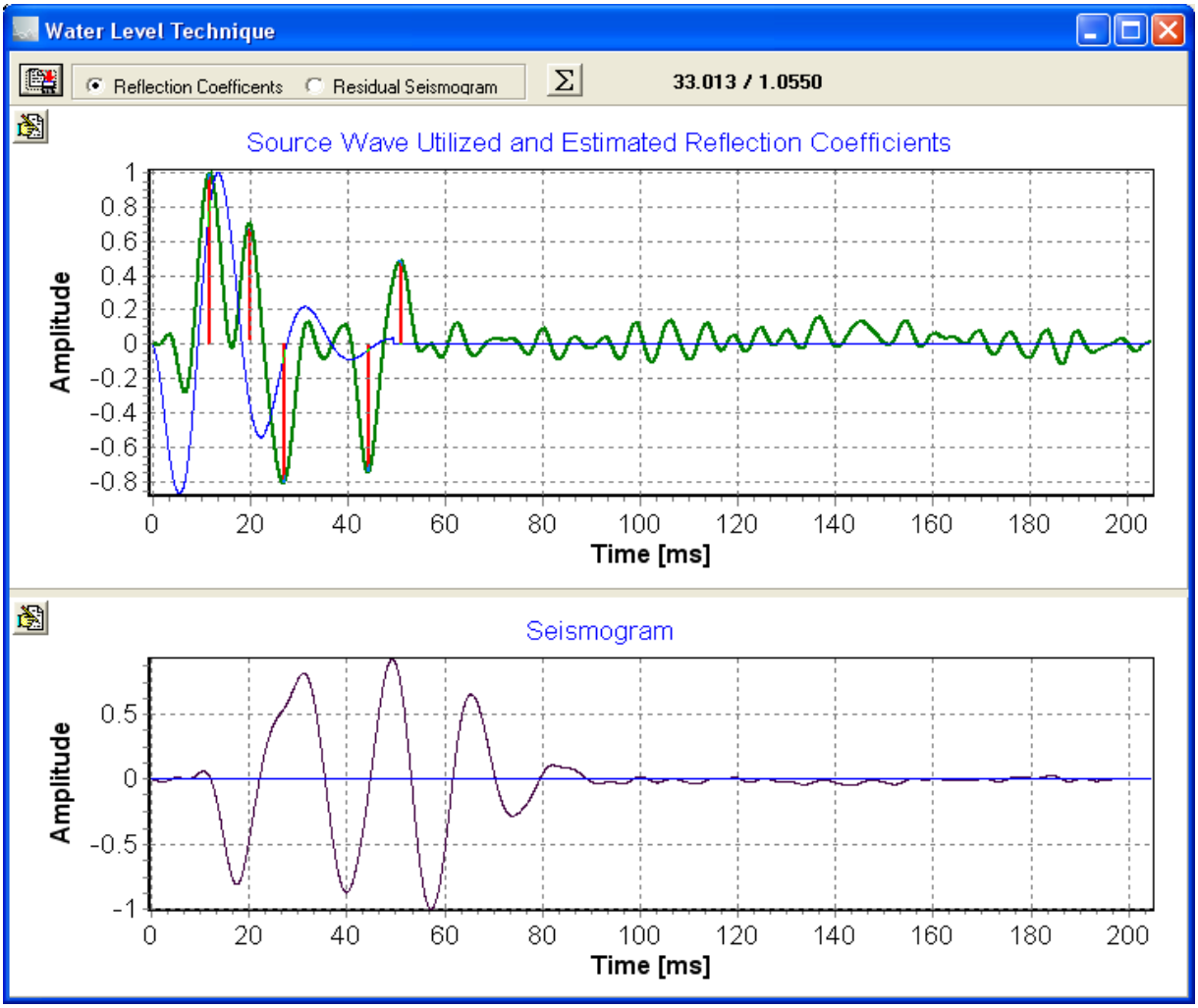

Figure 27: WLT output

The top chart of Figure 27 shows the estimated normalized reflection series and inputted and normalized source wave. The estimated and normalized reflection series is very similar in shape to that shown in Figure 13 but there is significant energy leakage where we have a bell shaped series. The bottom chart in Figure 27 illustrates the inputted seismogram which has been filtered with a 200 Hz low pas filter.

The WLT technique can initially be implemented until a time index, t^*, is identified where the reflection coefficients change shape (signifying source wave time variance [1]). The *PPD*™ algorithm can then be re-applied at time index t^* by moving the cursor in the top chart and then pressing the middle mouse button or <ctrl> + left mouse button or <ctrl> + right mouse button. The selected time index can be cleared by double clicking the left mouse button. For example, the time index at 35ms is selected in Figure 28. Pressing button will result in applying the WLT algorithm from $t = 0$ to $t = t^*$ with the inputted source wave and subsequently deriving the residual seismogram as is illustrated in Figure 29. The *PPD*™ algorithm can then be applied to the residual seismogram.

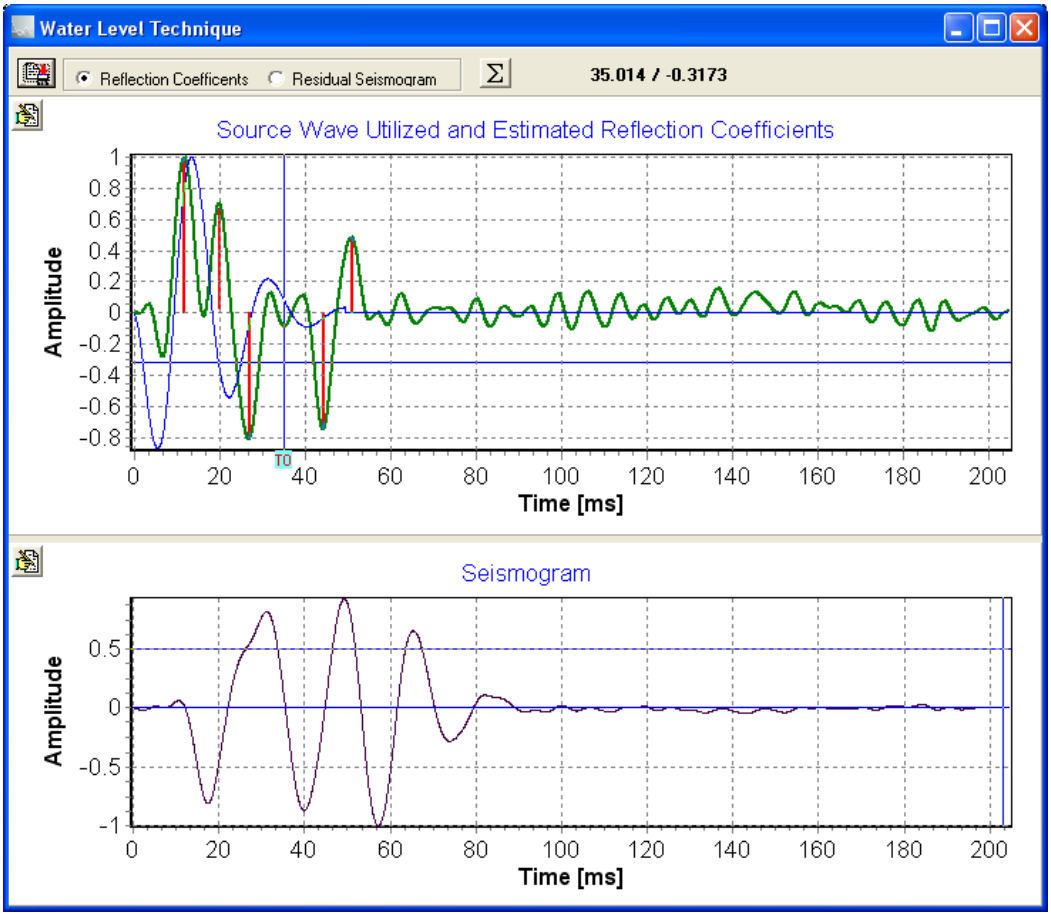

Figure 28: Selecting the reference time within the WLT algorithm so that the resdiual seismogram is derived

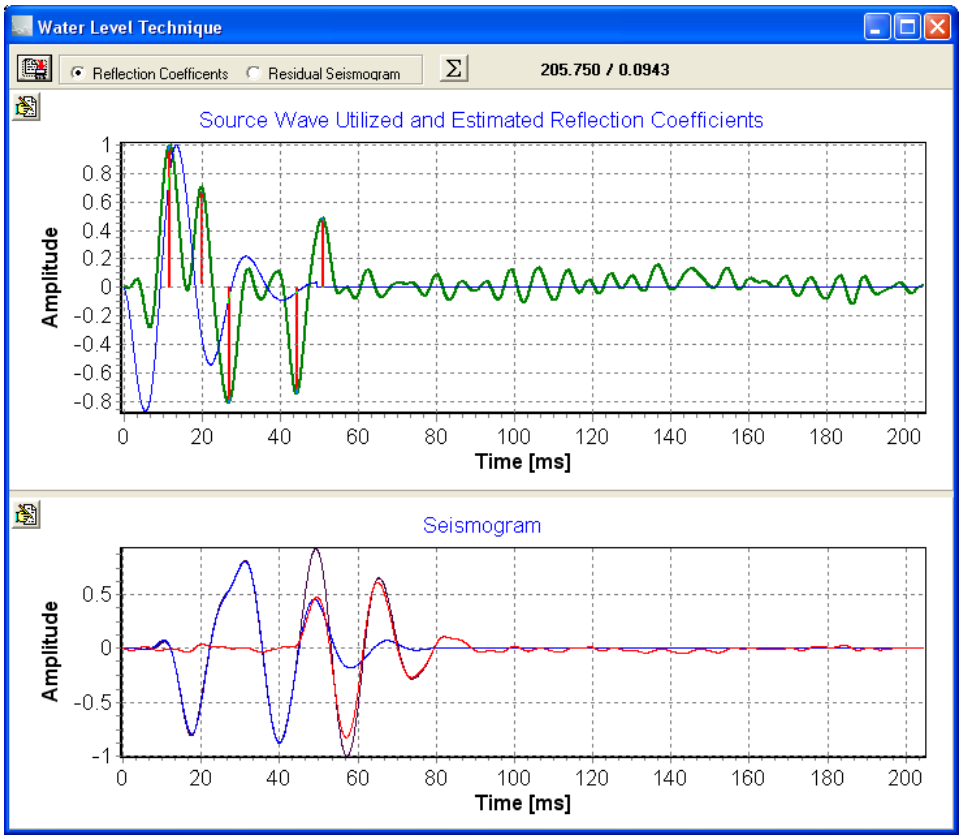

Figure 29: Residual seismogram illustrated as red time series in bottom chart

The estimated reflection series and residual seismogram can be saved by selecting the appropriate radio button (*Reflection Coefficients* and *Residual Seismogram*, respectively) and pressing button . The user is then instructed to specify the file name and directory as was illustrated in Figure 23.

5.0 Utilities

As illustrated in Figure 30, the *Utilities* menu option consists of the following sub-menus:

- *Sensor Type*
  to specify the sensor used to record the seismic data (i.e., accelerometer or geophone)
- *View Seismogram*
  to view a seismogram file and its corresponding frequency spectrum so that the appropriate type of digital frequency filters can be ascertained
- *VSP*
  to display Vertical Seismic Profiles (VSPs) and corresponding trend lines for downhole seismic investigations.

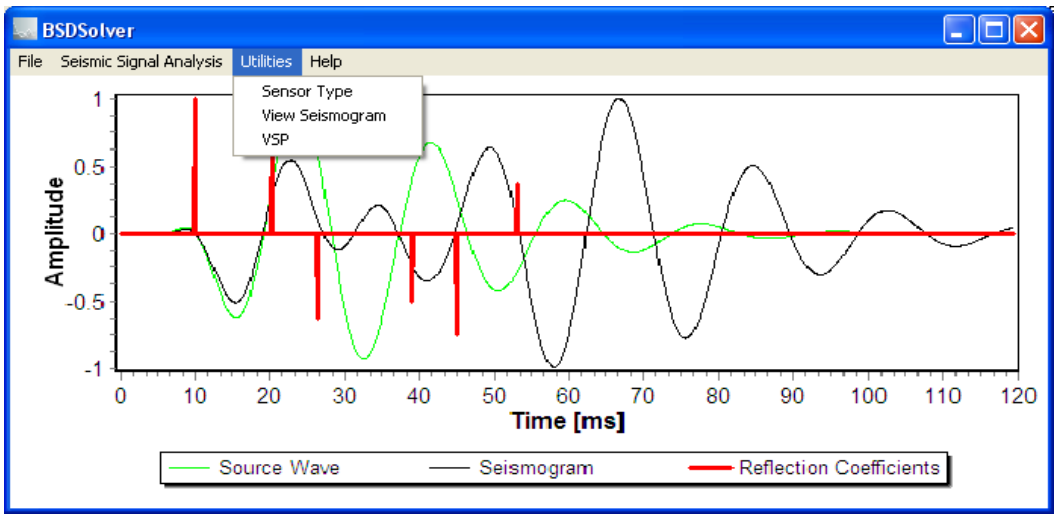

Figure 30: Utilities software options

5.1 Sensor Type

The *Sensor Type* dialogue box is illustrated in Figure 31. The user selects either an *Accelerometer* (output proportional to particle acceleration) or *Geophone* (output proportional to particle velocity). The user should specify the type of data to be processed prior to proceeding with the analysis options provided.

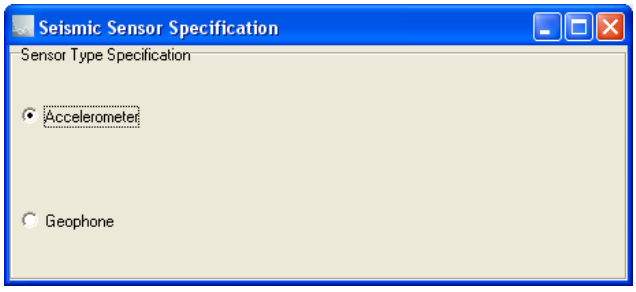

Figure 31: Sensor Type dialog box

5.2 View Seismogram

The *View Seismogram* software option allows the user to analyze a seismic file on an individual basis. Analysis features consists of filtering the seismic trace, overlaying the unfiltered trace onto the filtered trace, displaying the smoothed Fourier transform of either the unfiltered or filtered seismic time series and applying an exponential decay. The user is strongly encouraged to implement the *View Seismic* software option so that the appropriate source wave bandwidth (i.e., f_{min} and f_{max}) and frequency filters can be selected prior to implementing BSD and the WLT.

Upon selecting the *View Seismogram* option a file input dialog box appears (e.g., Figure 6) where the user is requested to specify the seismic file to process. Figure 32 illustrates the graphical output which appears once the appropriate seismic file has been selected. At the top of Figure 32 there are the checkboxes of *Filter*, *Overlay* and *FFT* as well as the numeric values of the time and amplitude at the current location of the graphical crosshair. If the *Filter* check box is selected the user interface illustrated in Figure 7 appears.

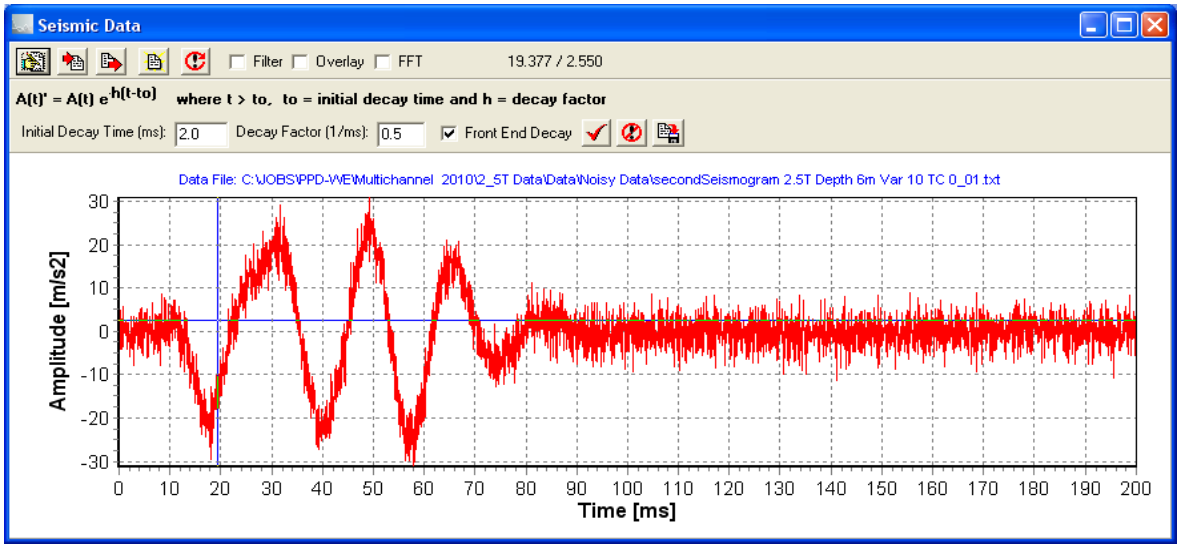

Figure 32: Main graphical interface in View Seismogram software option

Figure 33 illustrates the graphical results after specifying a low pass filter of 200 Hz. The user may then overlay the unfiltered seismic trace onto the filtered trace by selecting checkbox *Overlay* as illustrated in Figure 34. The smoothed Fast Fourier Transform (FFT) of either the unfiltered or filtered seismic trace is derived and displayed by selecting checkbox *FFT*. The frequency spectrum of the filtered trace is displayed if the checkbox *Filter* is selected along with the *FFT* checkbox. Otherwise the unfiltered seismic trace's frequency spectrum is displayed. Figure 35 illustrates the frequency spectrum of the unfiltered data file illustrated in Figure 32. Figure 36 shows the dominant frequency window (45Hz to 60Hz) for the frequency spectrum illustrated in Figure 35. This portion of the frequency spectrum was selected by pressing the right mouse button and panning left to right with the mouse. The user can zoom out to the original display by pressing the right mouse button and panning right to left with the mouse.

Selection of user interface button facilitates the user to read in a new data file. Button allows the user to re-filter the seismogram by redisplaying the *Filter Parameter Specification* user interface shown in Figure 7. Buttons and facilitate the user in saving the currently configured chart settings and loading previously configured chart settings, respectively.

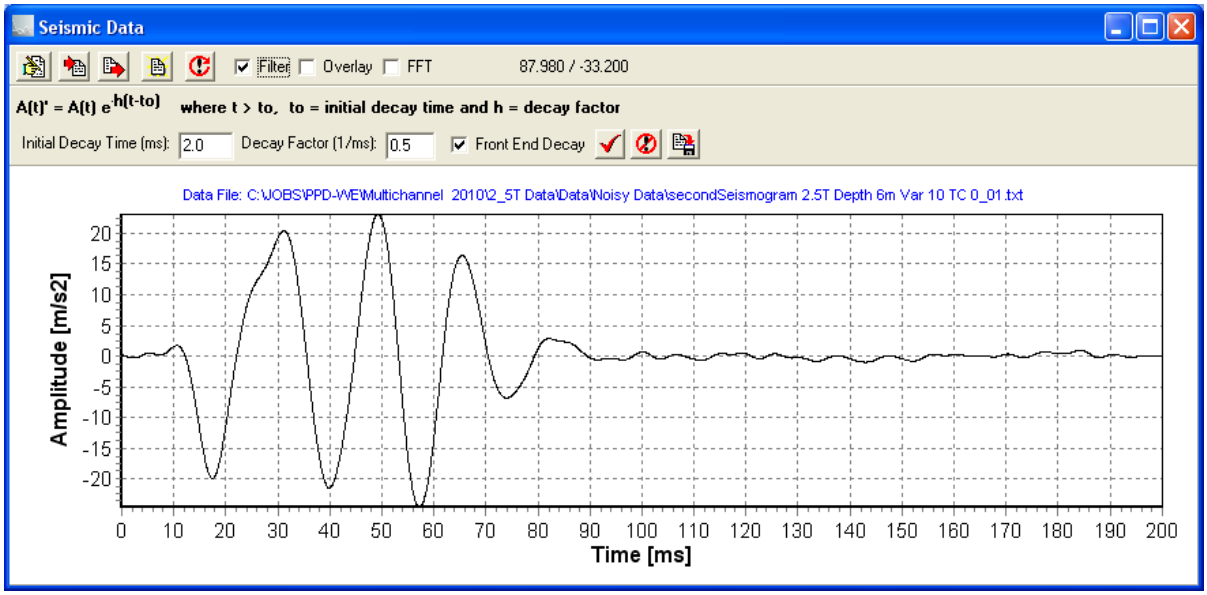

Figure 33: Filtered seismic trace in View Seismic in software option View Seismogram

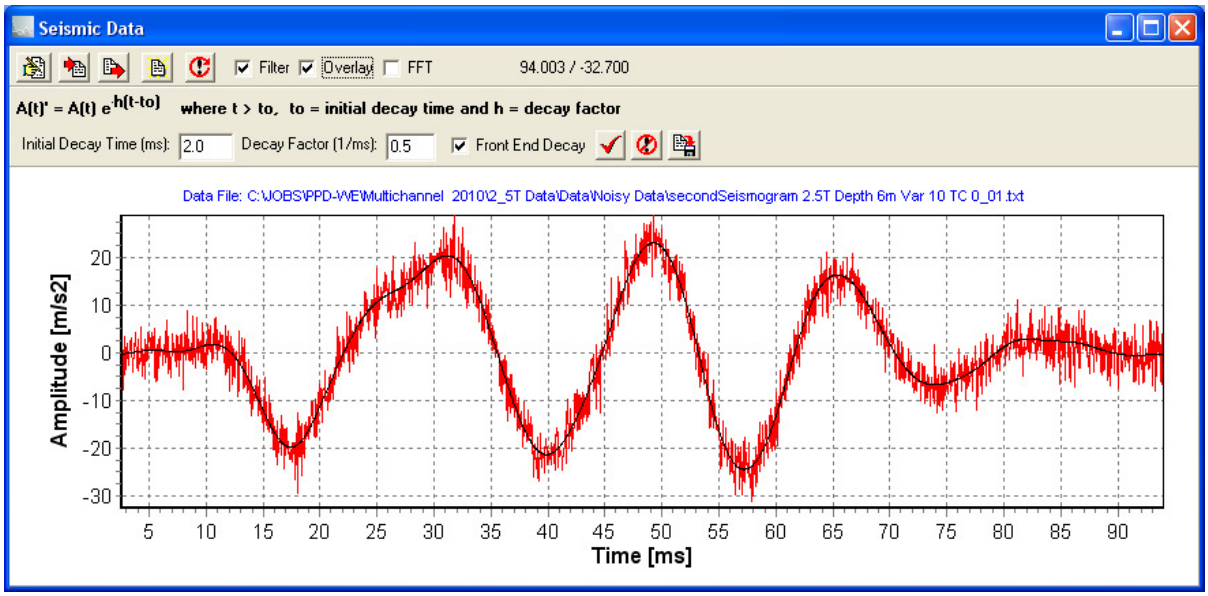

Figure 34: Overlaying unfiltered seismic trace onto filtered seismic trace illustrated in Figure 31

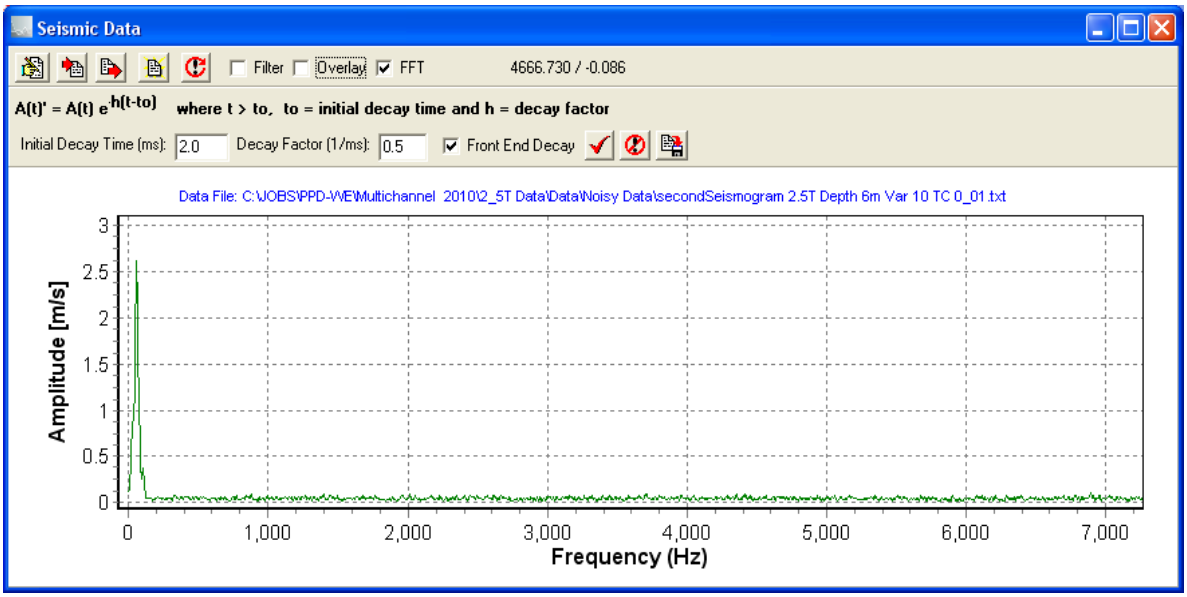
Seismic Data
Filter
Overlay
FFT
4666.730 / -0.086
A(t)' = A(t) e^h(t-to) where t > to, to = initial decay time and h = decay factor
Initial Decay Time (ms): 2.0
Decay Factor (1/ms): 0.5
Front End Decay
Data File: C:\JOBS\PPD-WE\Multichannel 2010\2_5T Data\Data\Noisy Data\secondSeismogram 2.5T Depth 6m Var 10 TC 0_01.txt
Amplitude [m/s]
Frequency (Hz)

Figure 35: Display of spectrum of seismic time series illustrated in Figure 30

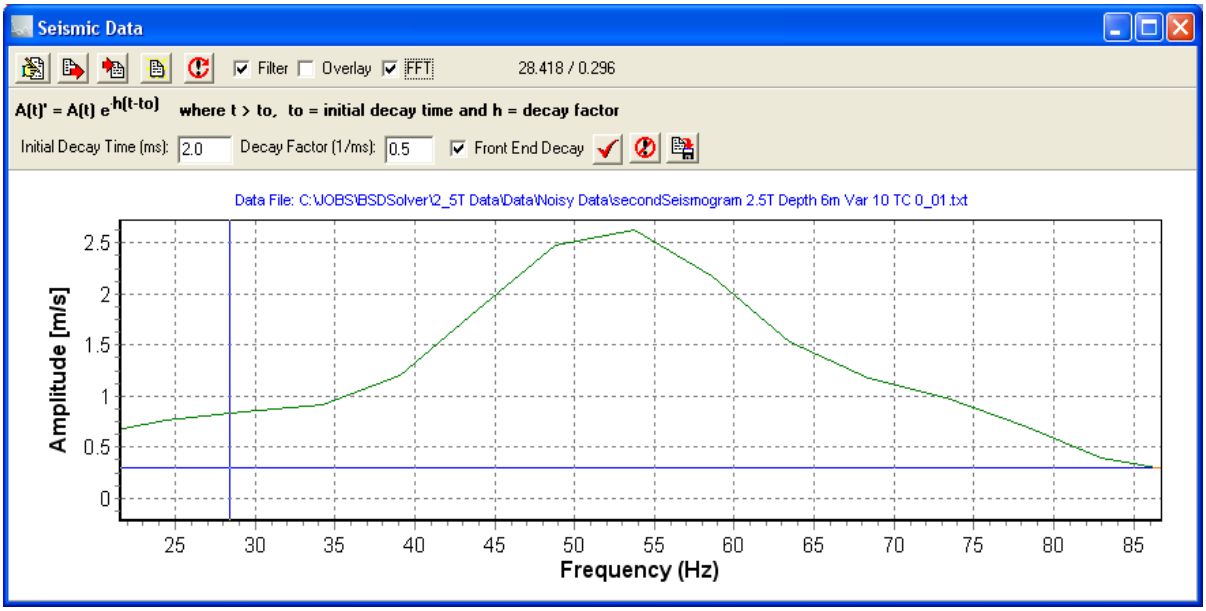
Seismic Data
Filter
Overlay
FFT
28.418 / 0.296
A(t)' = A(t) e^h(t-to) where t > to, to = initial decay time and h = decay factor
Initial Decay Time (ms): 2.0
Decay Factor (1/ms): 0.5
Front End Decay
Data File: C:\JOBS\BSDSolver\2_5T Data\Data\Noisy Data\secondSeismogram 2.5T Depth 6m Var 10 TC 0_01.txt
Amplitude [m/s]
Frequency (Hz)

Figure 36. Dominant frequency window (45Hz to 60Hz) for frequency spectrum shown in Figure 35.

When implementing the *PPD*™ algorithm it is important that the seismogram has an unambiguous first break or source wave arrival time (t_0). The *Signal Decay* option in *View Seismogram* facilitates the user in defining clear first breaks when they do not exist due to excessive measurement noise. The technique implemented to do this relies upon the application of an exponential decay that is applied to the selected time series data after a user specified time (the so-called *Initial Time Delay)*. The option therefore requires that the user specifies this *Initial Time Delay* (ms) and the *Decay Factor* (1/ms), which has a default value of 0.5/ms. As the *Decay Factor* is increased, there is a sharper decay of the time series data at the specified time index. If it is desired to decay from the start of the trace to the *Initial Delay Time* then check box *Front End Decay* must be checked. This is most likely the case as the purpose of signal decay is to clearly define the first break when it is not apparent.

Figures 37 and 38 illustrate a filtered (200 Hz low pass) seismogram data where there is a poorly defined first break. The *Signal Decay* option was implemented on the seismogram with the *Initial Time Delay* set to 13 ms and the *Decay Factor* to the default value of 0.5/ms. The *Initial Time Delay* of 13 ms was selected due to the fact that the seismogram appears to have a smooth decay until this time reference. Figure 39 illustrates the output after applying signal decay by pressing button . Selecting button undoes the previously applied signal decay and button facilitates the user in saving the filtered and front end decayed seismogram for further processing with the BSD and WLT software options.

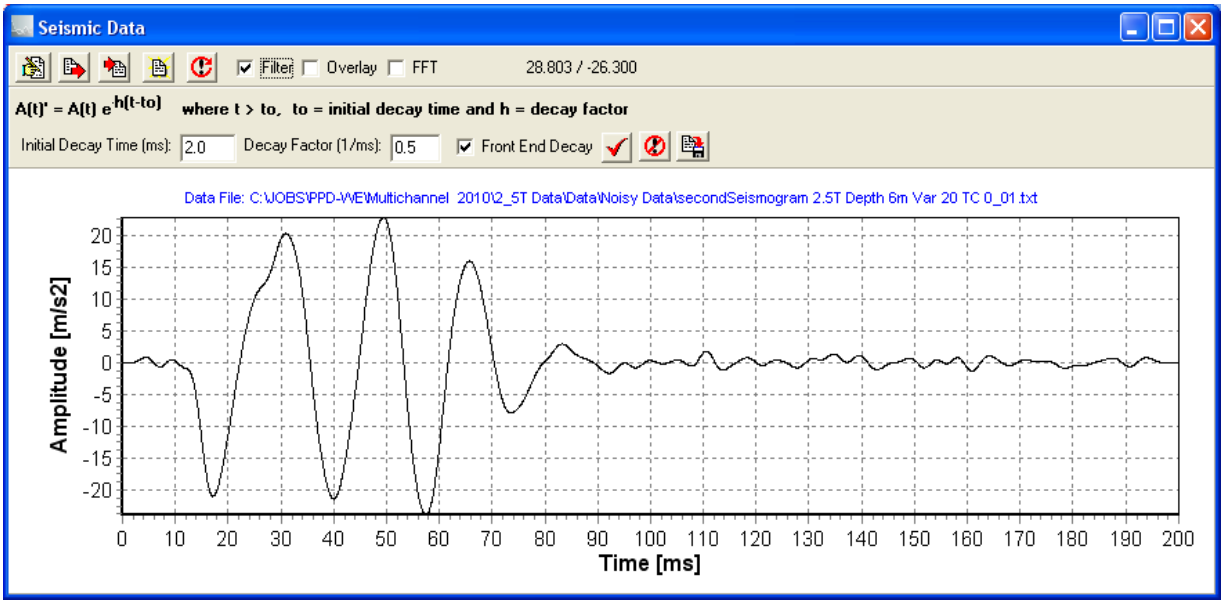
Seismic Data
Filter
Overlay
FFT
28.803 / -26.300
A(t)' = A(t) e^h(t-to)
where t > to, to = initial decay time and h = decay factor
Initial Decay Time (ms): 2.0
Decay Factor (1/ms): 0.5
Front End Decay
Data File: C:\JOBS\PPD-WE\Multichannel 2010\2_5T Data\Data\Noisy Data\secondSeismogram 2.5T Depth 6m Var 20 TC 0_01.txt
Amplitude [m/s2]
Time [ms]

Figure 37: Seismogram with poorly defined first break

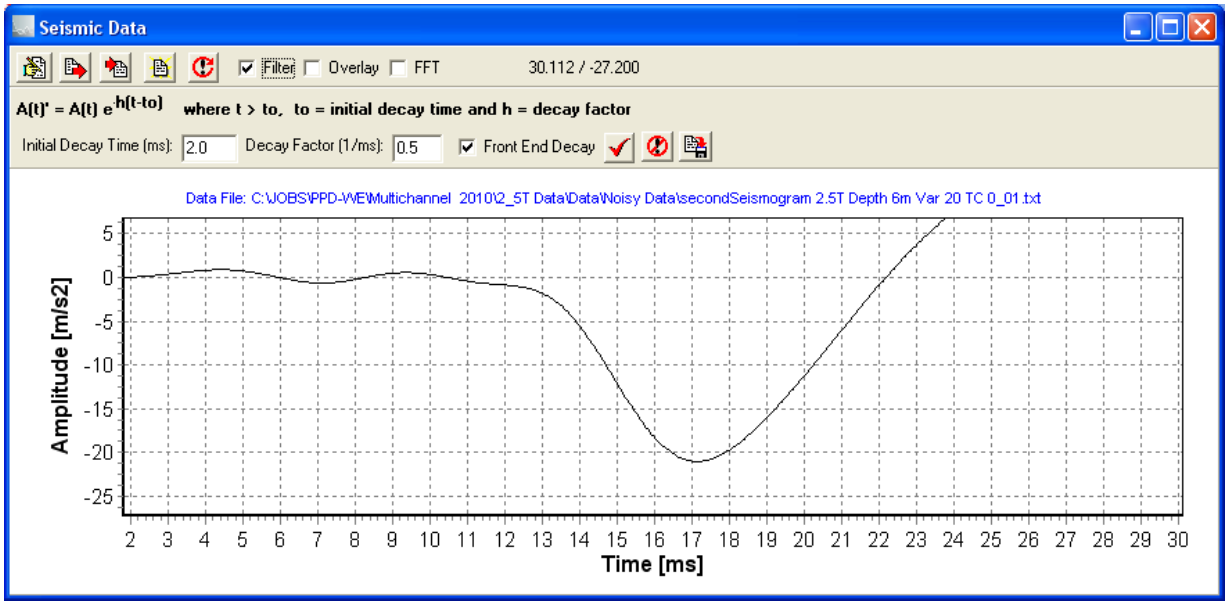
Seismic Data
Filter
Overlay
FFT
30.112 / -27.200
A(t)' = A(t) e-h(t-to)
where t > to, to = initial decay time and h = decay factor
Initial Decay Time (ms): 2.0
Decay Factor (1/ms): 0.5
Front End Decay
Data File: C:\JOBS\PPD-WE\Multichannel 2010\2_5T Data\Data\Noisy Data\secondSeismogram 2.5T Depth 6m Var 20 TC 0_01.txt
Amplitude [m/s2]
Time [ms]

Figure 38: Time window magnification of first break shown in Figure 34

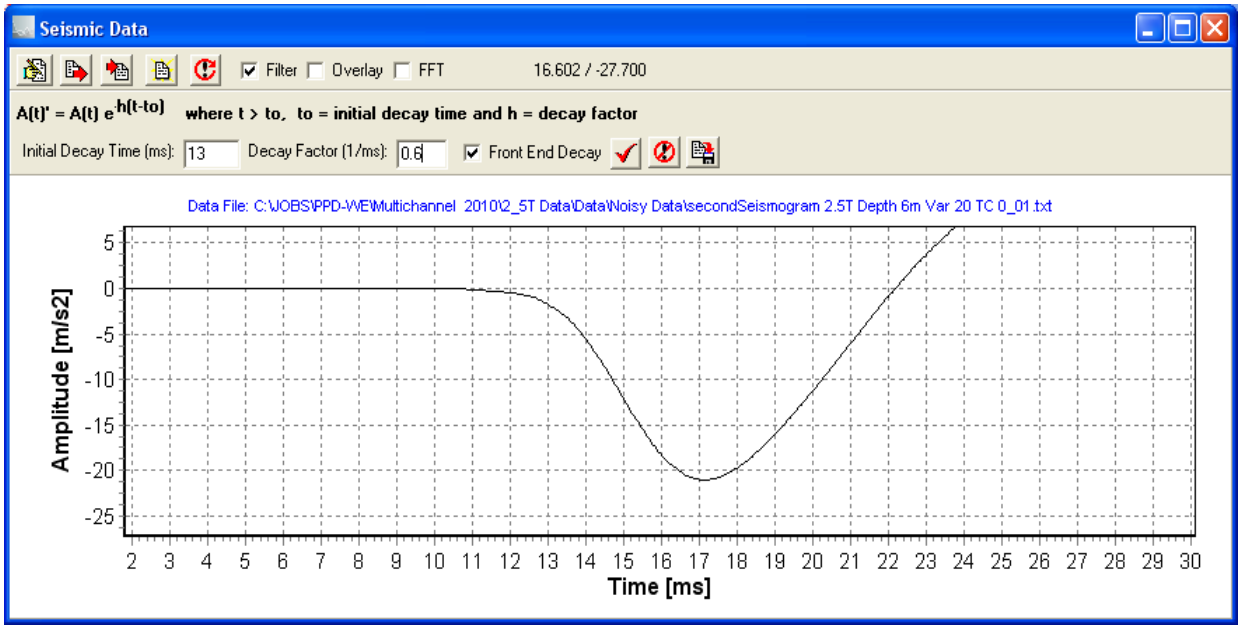
Seismic Data
Filter
Overlay
FFT
16.602 / -27.700
A(t)' = A(t) e-h(t-to)
where t > to, to = initial decay time and h = decay factor
Initial Decay Time (ms): 13
Decay Factor (1/ms): 0.6
Front End Decay
Data File: C:\JOBS\PPD-WE\Multichannel 2010\2_5T Data\Data\Noisy Data\secondSeismogram 2.5T Depth 6m Var 20 TC 0_01.txt
Amplitude [m/s2]
Time [ms]

Figure 39: Seismogram with front end decay applied

5.3 VSP

The *VSP* software option allows the user to plot filtered seismic traces or estimated reflection series in a two dimensional vertical seismic profile display. The VSP display provides a *Depth vs Time* plot where the user can specify interval velocity trend lines for preliminary velocity estimation. In addition, the user can display acceleration, velocity or displacement particle motions along with the peak particle accelerations, velocities or displacements, respectively.

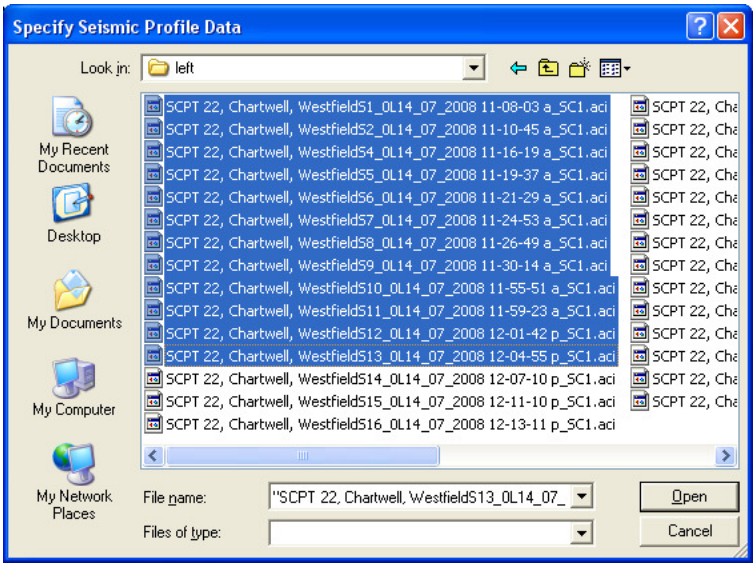
Specify Seismic Profile Data
Look in:
left
My Recent Documents
Desktop
My Documents
My Computer
My Network Places
SCPT 22, Chartwell, Westfield51_0L14_07_2008 11-08-03 a_SC1.aci
SCPT 22, Chartwell, Westfield52_0L14_07_2008 11-10-45 a_SC1.aci
SCPT 22, Chartwell, Westfield54_0L14_07_2008 11-16-19 a_SC1.aci
SCPT 22, Chartwell, Westfield55_0L14_07_2008 11-19-37 a_SC1.aci
SCPT 22, Chartwell, Westfield56_0L14_07_2008 11-21-29 a_SC1.aci
SCPT 22, Chartwell, Westfield57_0L14_07_2008 11-24-53 a_SC1.aci
SCPT 22, Chartwell, Westfield58_0L14_07_2008 11-26-49 a_SC1.aci
SCPT 22, Chartwell, Westfield59_0L14_07_2008 11-30-14 a_SC1.aci
SCPT 22, Chartwell, Westfield510_0L14_07_2008 11-55-51 a_SC1.aci
SCPT 22, Chartwell, Westfield511_0L14_07_2008 11-59-23 a_SC1.aci
SCPT 22, Chartwell, Westfield512_0L14_07_2008 12-01-42 p_SC1.aci
SCPT 22, Chartwell, Westfield513_0L14_07_2008 12-04-55 p_SC1.aci
SCPT 22, Chartwell, Westfield514_0L14_07_2008 12-07-10 p_SC1.aci
SCPT 22, Chartwell, Westfield515_0L14_07_2008 12-11-10 p_SC1.aci
SCPT 22, Chartwell, Westfield516_0L14_07_2008 12-13-11 p_SC1.aci
File name:
"SCPT 22, Chartwell, Westfield513_0L14_07_
Files of type:
Open
Cancel

Figure 40: File input dialog box

When the user selects *VSP*, the file input dialog box illustrated in Figure 40 appears. The user can input multiple seismic files in this dialog box (ie., <SHIFT> + left mouse click or <CTRL> + left mouse click). After specifying the files to be displayed, the *Filter Parameter Specification* user interface (i.e., Figure 7) appears facilitating the user applying the digital frequency filters to the selected seismic data files. Once the seismic data files and frequency filters are specified, a VSP appears as is illustrated in Figure 41.

The magnifying glass icons shown in Figure 41 allow the user to scale the seismic amplitudes in 10% increments. The legend can be added and removed from the display by checking and un-checking the *Legend* check box, respectively. The buttons and allow the user to automatically display and remove all the inputted data files from the graphical chart, respectively.

The user can display acceleration, velocity or displacement profiles by pressing the right mouse button and selecting the desired particle motion as shown in Figure 41. When the traces are not normalized, the peak particle accelerations (PPA), velocities (PPV) or displacements (PPD) are displayed. In this mode, the seismic amplitudes are scaled relative to the maximum amplitude within the seismic profile.

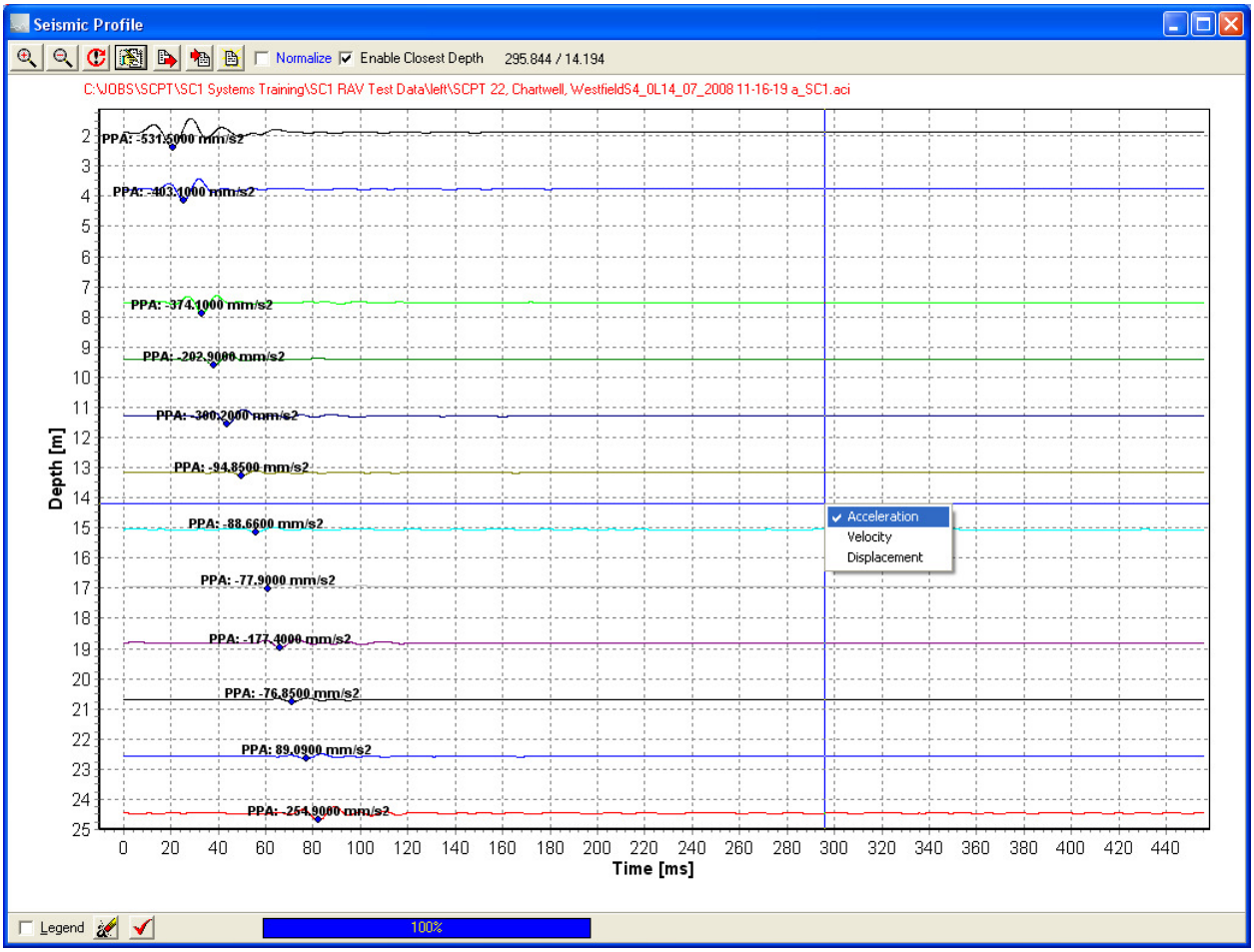

Figure 41: Filtered (30 to 100 Hz bandpass) seismic trace profile with peak particle accelerations (PPA) displayed

The trend lines illustrated in Figure 42 are specified by pressing the middle mouse button (or <shift> + right mouse button or <shift> + left mouse button) to identify individual points of interest. The *BSDSolver*™ program then automatically draws a line between the points specified and provides a velocity estimate[2]. Pressing options <Ctrl> + left mouse button or <Ctrl> + right mouse button will delete the previously specified trend line. Double clicking the middle mouse button will delete all the specified trend lines.

[2]**To obtain accurate interval arrival times utilizing the trend line specification, it is mandatory that the investigator select the appropriate time index at the exact depth of the probe from which the seismic data was recorded. Alternatively, if check box *Enable Closest Depth* is enabled the *BSDSolver*™ software relates back to the closest data depth when specifying trend lines.**

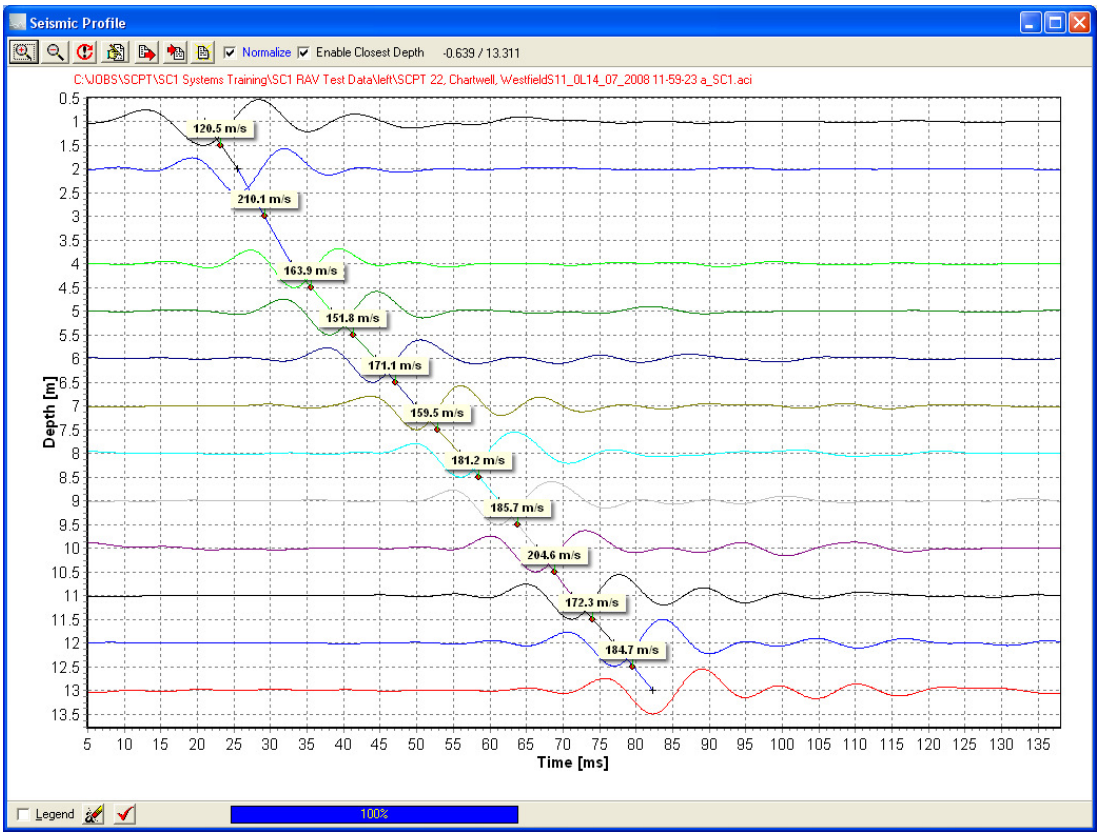

Figure 42: Filtered (30 to 100Hz bandpass) seismic trace profile illustrating trend lines with corresponding interval velocity estimates

6.0 Chart Formatting, Exporting, and Printing

The graphical edit button (e.g., Figures 19, 20, & 22) allows for chart formatting, printing, and exporting. Figure 43 illustrates the graphical interface that appears when this button is selected, which allows for extensive modification of the displayed data and chart attributes. In addition the data can be printed by selecting the *Print* tab, which brings up the *Chart Printing Dialogue Box* as shown in Figure 44. Finally, this utility has an extensive electronic Help function, which is accessed though the H*elp* button at the bottom left of the screen.

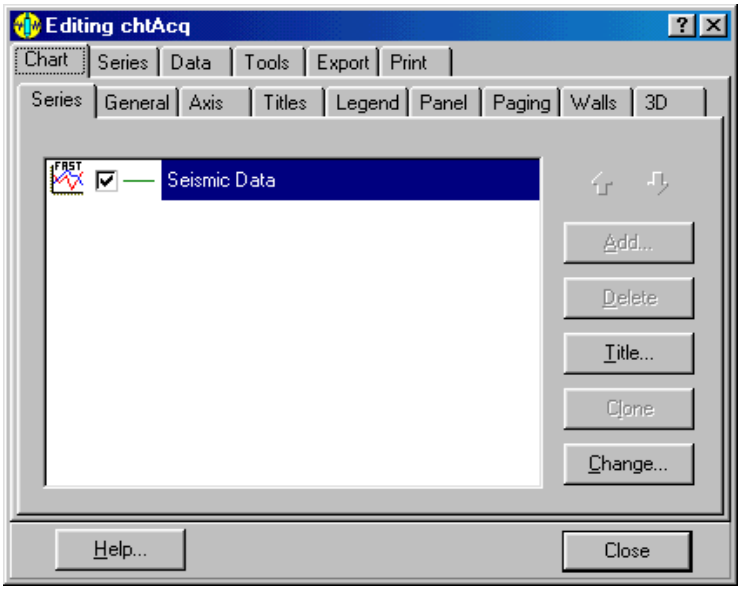

Figure 43: Chart Editing Dialogue Box

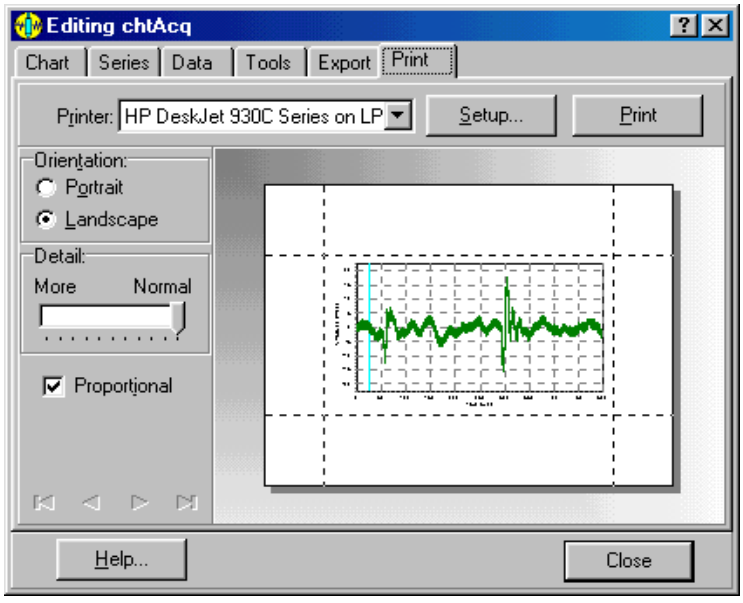

Figure 44: Chart Printing Dialogue Box

7.0 Help Menu

The main menu shown in Figure 1 includes a *Help* option that includes the following:

- **About** - provides software version information on ***BSDSolver™***.
- **User's Manual** - will output the ***BSDSolver™*** user's manual in a default pdf browser.
- **Appendix 1** – will output the paper entitled "Incorporation of Iterative Forward Modeling into the Principle Phase Decomposition Algorithm for Accurate Source Wave and Reflection Series Estimation" in a default pdf browser.
- **Appendix 2** – will output the paper entitled "Implementation of the Principle Phase Decomposition Algorithm" in a default pdf browser.
- **Appendix 3** – will output the paper entitled "Principle Phase Decomposition - A New Concept in Blind Seismic Deconvolution" in a default pdf browser.

References

1. Baziw, E., “Incorporation of Iterative Forward Modeling into the Principle Phase Decomposition Algorithm for Accurate Source Wave and Reflection Series Estimation”. to be published in the IEEE Transactions on Geosci. Remote Sensing, 2010.

2. Baziw, E., "Implementation of the Principle Phase Decomposition Algorithm", IEEE Transactions on Geoscience and Remote Sensing (TGRS), vol. 45, No. 6, pp. 1775-1785, June. 2007.

3. Baziw, E. and Ulrych, T.J., "Principle Phase Decomposition - A New Concept in Blind Seismic Deconvolution", IEEE Transactions on Geoscience and Remote Sensing (TGRS), vol. 44, No. 8, pp. 2271-2281, Aug. 2006.

4. Amini, A. and J.A. Howie, T.J., “Numerical simulation of downhole seismic cone signals”, Canadian Geotechnical Journal, vol. 42(2), pp. 574-586, 2005.

5. E. Baziw, “State-space seismic cone minimum variance deconvolution”, In Proceedings of the 2nd International Conference on Geotechnical Site Characterization (ISC-2), vol. 1, pp. 835-843, Porto, Portugal: Millpress Science Publishers, 2004.